sail

Sail into a sustainable future

Roadmap for Sail Transport: Engineering

European Union
The European Regional Development Fund

The Interreg IVB North Sea Region Programme

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provincie fryslân

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Roadmap for Sail Transport: Engineering
Workpackage 3
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CONTENT

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1   Introduction

This report sketches a strategy to include wind propulsion systems into the standard design and building process of commercial cargo ships, it is part of the results of the SAIL project, an INTERREG project of the North Sea Region (NSR). This project focuses on hybrid ships, these are ships equipped with a combination of conventional and wind assisted propulsion (WASP). There are several reasons for using hybrid ships: on a long term view the search for alternative drives is stimulated by the finite resources of conventional fuels, to put it shortly sustainable shipping requires use of sustainable energy sources. But even today hybrid ships are more and attractive for different reasons. The dramatic increase of fuel prices in the last decades makes hybrid ships more and more economically feasible. And hybrid ships help to achieve the emission reduction goals which are laid out for instance in the IMO regulations like the MARPOL ANNEX VI. The SAIL project builds a roadmap for using hybrid ships in the near future. It uses a very broad approach to study potentials and drawbacks of hybrid shipping technologies, identifies obstacles and how to remove them. In total the project shows up how the change to sustainable and low-emission sailing can be facilitated. The broad approach is reflected in the project's work package structure,

- WP1: Planning and Tracking
- WP2: Publicity
- WP3: Engineering
- WP4: Economy
- WP5: Policy and Legislation
- WP6: Private Public Alliances

The work package 3 decided to write this collaborative report to summarize the results of the individual activities within our work package. This report is targeting different audiences. We want to show stakeholders that ships with sails are not historical devices from the good old times but modern logistic solutions that fit into today's shipping economy. We want to prove that constructing and building a hybrid sailing ship is not an adventure but merely state-of-the-art engineering. And we want to show that the design process for hybrid ships is rather straight forward. Another target group are engineers and naval architects: we sketch the extra steps required for designing a hybrid ship, we present methods to estimate the performance of wind assisted ships and give examples for detailed constructions. Note that this document does not create a timeline for wind assisted propulsion, instead it is shown that technology and design techniques for hybrid ships is available today.

The next section gives some motivation to deal with hybrid shipping, the environmental impact of sea transport is roughly discussed and overview of recent developments of ships under sails is given.

The subsequent sections deal with various aspects of designing a hybrid ship. The design of ships is an iterative process: ad-hoc decisions have to be taken in early design stages based on the knowledge available at that time, these decision are refined or corrected during the design process. This procedure is usually depicted by the so-called design spiral, the special features of a design spiral for hybrid ship is discussed in section 3. In early stages of the design basic specifications like ship type, size, operational area and speed are defined. A preliminary choice of powering is important here as engines and sails have to be integrated into the body plan. At this stage the ratio of wind power to conventional power is fixed, type and size of the wind propulsion system and the engine are chosen. It should be noted that this design stage lacks information required for a detailed performance analysis, it would for instance be nice for instance to calculate the wind generated fuel savings. But such calculations require resistance data of the ship hull which is not available since the hull is not drawn in detail.

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It was found in the project that in this design stage a tool for estimating and comparing the performance of different rigs is very useful. Therefore a program was developed that estimates the wind generated power for a given propulsion system on a given route. The program uses a rather simple algorithm and is therefore very fast. This allows to compare many different configurations and find a viable solution. The program is explained in section 4, many simulation results are found in the roadmap[1]. The basic input for this program are lift and drag coefficients of the wind propulsion system.

Data for many modern wind propulsion systems is collected in the wind propulsion catalogue in section 5. The catalogue shows that various options with different advantages and disadvantages are available. The decision for a particular drive depends on several criteria. Some of these criteria are specified by numbers and are easy to decide on. Other factors like "operability" are soft, they are not easily quantified by numbers. A list of soft criteria was made in several work package meetings and put together in a score matrix which is described in section 5. The rationale behind the score matrix and how to use it properly is explained in section 5 as well.

The result of the first iteration on the design spiral is the conceptual design. Citing a contemporary book on ship construction, a concept design should provide "sufficient information for a basic techno-economic assessment of the alternatives to be made."[2] What this means is shown on an example, the "Flettner Freighter" developed by C-Job within the SAIL project in section 6. Another important design is the Ecoliner[3]. The Ecoliner is designed by Dykstra Naval Architects, it features a 8000 DWT multi purpose cargo vessel equipped with three mast equipped with a Dynarig. In order to evolve this promising design operational and aerodynamic characteristics were studied in the SAIL project and can be taken here as a showcase. With a conceptual design detailed information of hull, general arrangement, engine and wind propulsion system is available. This allows to study the operational performance on a more detailed level by simulating voyages. Extensive voyage simulations are performed for the Ecoliner in section 9. The input for the voyage simulations is detailed performance data of the projected wind propulsion system including for instance the interaction of the sails with the superstructure. Such data can be obtained by computer simulation (CFD calculations) or wind tunnel tests. Wind tunnel tests for the Ecoliner were done by the SAIL project. These are described in section 7. Another important set of data for voyage simulations is the hull performance. These data are usually collected in towing tank experiments or determined by CFD calculations. CFD-resistance for another concept, a 3000 TDW freighter are shown as an example in section 8.

While sail ships have a long tradition, there is space for new concepts and innovation. Such concepts convince if there is a practical test on a ship: the ship acts as a living lab. In section 10 some concepts are described and a living lab is introduced.

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[1] Bonduelle, Metivier, Rynikiewicz: Roadmap for Sail Transport, published within the Interreg SAIL project, 2015
[2] Eyres, Bruce: Ship Construction, Elsevier, 2012
[3] Dykstra: The Ecoliner concept, http://www.marin.nl/web/file?uuid=000bd829-eeea-4479-bc80-a1ba27fc8cb4&owner=bbe0c94c-375d-4ae8-b452-251a414c25d7

2 Hybrid shipping

Ships are subject to emission reduction goals. Does that mean that sea transport should be avoided for ecological reasons? Well, in Fig. 2.1 the contributions of the individual carriers to transport related emissions are shown[4]. Shipping creates a considerable contribution to the greenhouse gas CO_2 with the well known impact on climate change. Nitrogen oxides (NOx) impact ecosystems and human health: they create acid rain and give rise to the creation of smog. In particular, NOx emitted from ships is a considerable and unwanted source of nitrogen in marine ecosystems which leads to eutrophication. Different techniques are available to reduce the emission of NOx, ranging from modifying engine components to cleaning the exhausts in a catalytic reactor. All these techniques create extra costs in terms of material investments, running costs and efficiency reduction. Sulphur oxides (SOx) shown in the third column in Fig. 2.1 lead to acidification of the environment. The sulphur required for the creation of SOx is found in the relatively cheap fuel used in shipping. Therefore IMO regulations limit the amount of sulphur in ship. Again extra costs are to be expected. Particulate matter (PM) denotes fine particles that are able to accumulate in the lung and penetrate into the cardiovascular system leading to various respiratory and cardiovascular diseases. However, even today's ships are unbeaten considering emissions per ton and mile: ships are ecologically friendly. Anyway their share to global transport is huge enough to make shipping a strong contributor to transport related emissions as shown by Fig. 2.1. So we come to the conclusion that improving the environmental performance of shipping is a good way to reduce global emissions, it is worthwhile to invest into better ships. Sails can be an option to reduce emissions by reducing fuel consumption.
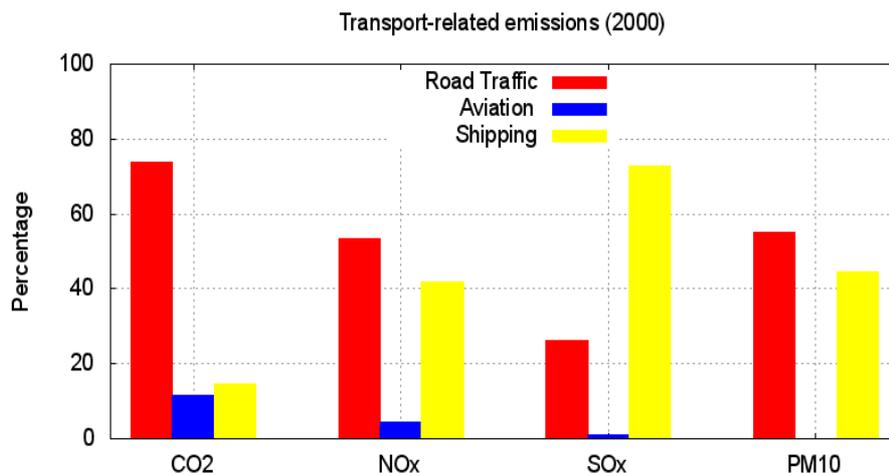

Fig. 2.1: Contributions of different transport carriers to emissions. Data from: Eyring et al. (2005).

Quite frequently people say that "the good old times of sailing ships" are gone, knowledge on building sailing ships is lost and ships under sails do not fit into modern shipping. Well, knowledge is not lost. In fact there is a continuous development of the aerodynamic properties of sails driven for instance by the yacht builders, a huge number of publications[5] and textbooks[6] do exist. There are lectures on the

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[4] Data are taken from Eyring et al.: Emissions from international shipping, J. Geophys. Res., 110, D17305, doi:10.1029/2004JD005619

[5] a relatively recent review is given in Viola: Recent Advances in Sailing Yacht Aerodynamics,

performance of sails and hulls in the education of naval architects[7]. Design and performance of cargo sailing ships is topic of special lectures[8]. In addition there is a continuous flow of studies for wind assisted commercial shipping. Many of these studies are triggered by a sharp rise of fuel prices, so the oil crisis the 1970s triggered several general studies e.g. [9,10]. While continuous interest remained on the subject, an increasing number of publications is found in the last years e.g.[11,12]. Several concepts have developed to a rather advanced level, for instance the Bremer Vulkan shipyard developed a concept study for a sail cruiser named "Pinta" with a Dynarig[13]. An example for a newer concept is described here[14]. Beyond concepts there were real ships proving the viability of hybrid ships. For instance the Japanese "Shin Aitoku Maru" was the first ship of a fleet of freighters with rigid wing sails (Fig 2.2). These ships operated well and within the specifications[10].

Another common belief is that hybrid ships need a huge crew to operate the sails, probably the old windjammers come into mind. A look at current hybrid ships tells a different story: modern rigs are computerized and controlled from the bridge, no extra crew is required. This is true for new sail systems like the Dynarig discussed in section 7 but also for more traditional rigs like the hybrid cruise ship "Wind Surf" (Fig. 2.3).

So from the Engineering point of view hybrid shipping is an established technology. Case studies show that wind assisted ships are economically viable at least in niche markets. So one might ask: "Wind propulsion for ships, why there are so few?" A few comments are given in[15], detailed roadmaps are found in the report of work package 4.

Applied Mechanics Reviews, Vol. 65, 2013

[6] for instance Fossati, F., Aero-Hydrodynamics and the Performance of Sailing Yachts, Adlard Coles Nautical, England, ISBN 978-1-4081-1338-7

[7] e.g. SD2706 Sailing for performance at the KTH Sweden

[8] e.g. Technical Elements and Fluid Mechanics of Sailing Ships, Peter Schenzle, TU HH, Hamburg-Harburg

[9] Wellicome, J. F.: A broad appraisal of the economic and technical requisites for a wind driven merchant vessel, Ship Science Reports 3, University of Southampton, 1975

[10] Bernaerts and Kurmis: Basics for the usagae of wind propulsion in board sea-going ships, Tech Report, HSVA, Hamburg, 1980

[11] Kazuyuki Ouchi et al.: "Wind Challenger" the Next Generation Hybrid Sailing Vessel, Proc.: Third International Symposium on Marine Propulsors smp'13, 2013

[12] Traut et al: Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes, Applied Energy 113, 2014

[13] Helmut Risch, Jochen Berthold: Windschiffe, VEB Verlag Technik Berlin, 1990

[14] Burdon et al: Fast Sail Assisted Feeder Container Ship, Proc.: Marine Unconventional Design Symposium – MUDS, 2010

[15] Gernez: Wind propulsion for ships in 2010: Why so few, Tech Report Det Norske Veritas, 2010

Fig. 2.2: The "Shin Aitoku Maru", a successful hybrid driven ship from the 1980s. (Photo: Mkmillenium. CC BY-SA 3.0)

Fig. 2.3: The „Wind surf" has a rather traditional rig which is completely computerized and does not require extra crew. (Photo: Didier Descouens, CC BY-SA 4.0)

3   Wind assisted ships and the design spiral

Concept design or engineering is done by integrating different disciplines or stages. These stages require input from one another. In many cases two stages are depending on each other for information. Therefore knowledge based assumptions must be used first to initiate the stages. This process repeats itself a couple times until the input and result of every stage is consistent with one another.

Most of these knowledge based assumptions have been obtained from previous done (specific) designs. For hybrid concepts the layout of these stages is more complicated. There is an additional stage in comparison to the stages of a conventional design in the form of the WASP (Wind Assisted Propulsion) engineering, which is similar to the mast and rigging engineering for a sail ship. Because the WASP hybrid design is a compromise between a conventional freight ship design and a sail ship the design spiral of the WASP hybrid design will be a combination of the design spiral used for a conventional freight ship and a design spiral used for a sail ship. This results in a spiral as seen in the Fig. 3.1. Some of these stages require additional attention when designing a WASP hybrid design in comparison to designing a conventional freight ship.
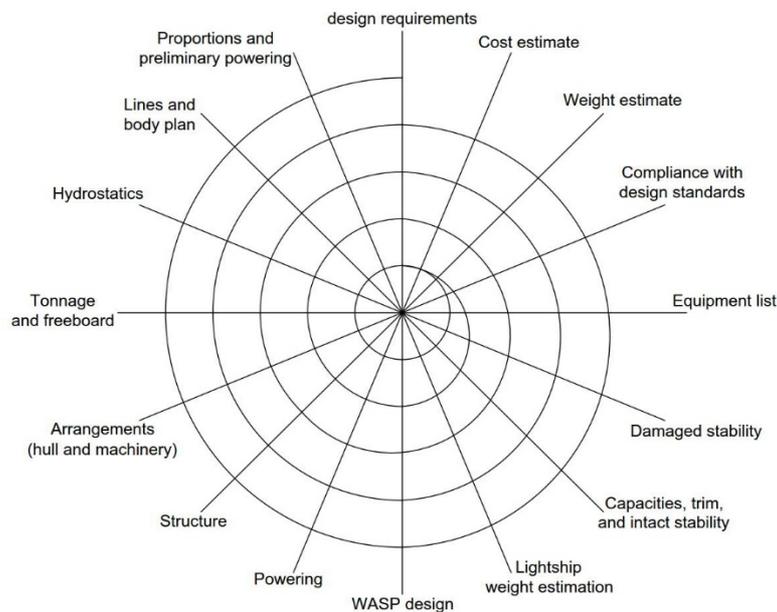

Figure 3.1: Design Spiral (http://pkboatplans.blogspot.nl/2011/11/design-spiral.html)

Design requirements

The mission requirements describe what the client wants or needs. For a freight ship design the cargo capacity, service speed and the operation region are of importance. This is even more important for a hybrid design that uses a WASP, because the wind speed is not a constant the average service speed and the region are to be considered more. The WASP installation reduces the weight and space for cargo as well.

Proportions and preliminary powering

The dimensions have impact on the resistance and the gross tonnage and thus the costs. The proportions describe the ratio between the different dimensions to obtain a reliable design. This is

often based on comparison ships. For a hybrid design this is more difficult because such comparison ships are not widely available.

Lines and Body Plan and Hydrostatics

The hull form must be optimized for the leeway (and heel) induced resistance due to the WASP, if the contribution of the WASP is considerable. The shape of the hull should be able to generate side force efficiently. Flat (shallow and wide) sections are to be avoided. The hull form is therefore typically different than for a conventional ship. Ships may require a skeg and or appendages, particularly in the aft region, also to realise a favourable steering balance, where the use of large rudder angles is not continuously required. At the same time stability should be sufficient in order not to continuously attain large heel angles.

Tonnage and freeboard

The tonnage and freeboard calculation should be done in an early stage to ensure that the hull form with the proportions is realistic. These calculations are necessary to fulfill class criteria and to provide info about harbor dues. This stage will not differ much between the conventional design and a hybrid design.

Powering

The installed power must be adequate to obtain an average service speed or a constant service speed for a specified range and region. For a WASP hybrid design the input of wind data should be used for that region.

Lightship weight estimation

The optimized hull form and the added construction of the WASP to the hybrid design results in a different ratio between the lightship weight and the deadweight. This different ratio has an impact on the stability and monitoring the weights is of importance.

The amount of steel in the design has an impact on the material costs, while the complexity of the construction has an effect on the labour costs. Thus the lightship weight and specifically the steel weight gives an indication of the costs when compared with other ships.

Capacities, trim, heel and intact stability

Due to the added forces from the WASP the hybrid design should be checked for trim and heel. The optimized hull form and higher COG must be considered when checking the intact stability.

Drift is the result of the balance between the WASP side forces and the underwater body side forces. This is present with sail ships or hybrid WASP designs as opposed to conventional designs. The amount is a compromise between the position on the deck of the WASPs and the added resistance due to drift.

Cost estimates

The cost estimation includes the operational, maintenance and constructional costs. This is an important stage for a hybrid design because the added WASP equipment costs and the maintenance costs must be in balance with the (additional) profits as well as the savings on the fuel costs.

4 Wind potentials

Performance estimates are an important indicator for the design quality. There exist sophisticated software tools like Gulliver of MARIN which is used section 9 to estimate the performance of the ship on a very detailed level. Such tools generally simulate ship voyages under realistic conditions, environmental conditions are taken from wind, wave and ocean current databases. These tools then optimize shipping routes, sheeting and reefing of sails, consider the heeling angle of a ship and variable speeds. These tools give good results if there is reliable data on hull- and aerodynamic performance. For given setup this performance data can be obtained from towing tank and wind tunnel tests or CFD-calculations. All this data is not available in the early design stages when basic decisions are to be taken.

For this situation a tool was designed in work package 3 that estimates the wind generated power on a given route and for a given wind propulsion system. Power and fuel reductions can be assessed roughly on the base of estimated wind power. The tool is fast running, open source and platform independent. This program uses a very simple model: it is assumed that the vessel travels at constant speed. The path is given by a set of waypoints, there is no route optimization. The sails are included by tabulated values of thrust- and lateral-force coefficients for different apparent wind angles. The wind conditions are looked up in a wind database.

The tool allows to compare
- wind potentials on different routes,
- different wind propulsion devices,
- different target speeds and
- combinations of all the above.

As a by-product statistics on the angles of attack of the apparent wind are created. This information helps to choose the appropriate wind propulsion device. The next sections installation and usage of the program are described. The algorithm is explained in section 4.4. Input and output files for deeper analysis are described in section 4.5. Some test cases are studied in section 4.6.

4.1 Program installation

The main program and the calculation routines are written in the scripting language R[16], the GUI uses the tcl/tk-package of R. The program is delivered as a zip file containing the programs itself and several directories for input, output, polar data and a placeholder for the wind database. Data are read from and written to these directories. The first step of the installation is to unpack the zip file to directory with write access. This directory will be denoted by PROG_DIR in the following documentation.

The next part of the installation is to get a running R-interpreter with a tcltk- and the netCDF-package. The procedure is described for Linux and Windows separately in the next sections. If you plan to read/modify the programme code, you might consider installing Rstudio which is an integrated development environment (IDE) for R available for both platforms. It includes syntax highlighting and a debugging function.

Next a wind database is needed, suitable data is available at European Centre for Medium-Range Weather Forecasts (ECMWF). In section 4.2 the procedure to download these data is explained.

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[16] http://cran.r-project.org/

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4.1.1 Linux

The programme utilizes a graphical user interface which requires X11 support. The following packages are required (Ubuntu package names given in brackets): the R interpreter with tcl/tk and netCDF4 support (R-base-dev, r-cran-ncdf4), the netcdf4 library (libnetcdf-dev), tcl/tk with some extensions (tcl-dev, tk-dev, tk-table, bwidget).

To install the needed packages on Ubuntu the packages can be installed via the Terminal by typing:

- sudo apt-get install libnetcdf-dev tcl-dev tk-dev tk-table bwidget
- sudo apt-get install R-base-dev r-cran-ncdf4

In order to test the installation, open a shell and start R by typing "R". Within R, type:

- setwd('PROG_DIR')
- source('standalone.R')

The GUI should open now. Here "PROG_DIR" denotes the directory with the file standalone.R.

The packages should have similar names on other Linux distributions. Some packages, in particular r-cran-ncdf4, may not be available as pre-compiled packages for older Ubuntu versions or for other Linux distributions. In this case manual compilation might be required. In order to install the ncdf4 package for the R interpreter (r-cran-ncdf4) manually

- start R in a terminal,
- from within R type "install.packages('ncdf4')" and
- choose a mirror in the pop-up window

If you get an error on missing writing permissions, quit R by typing "q()", start R again as super user by "sudo R" and type "install.packages('ncdf4')", again.

4.1.2 Windows

The zip-file for Windows includes an R-interpreter and the required libraries. After unzipping the file there will be a folder "WindPotentials-Windows" with the program itself (standalone.R, standalone.tcl, some ppm-files), a link to the R-interpreter R.exe and several directories. The link to the R-interpreter has to be updated to point to WindPotentials/R-3.1.0/bin/R.exe. Now start the R-interpreter by double-clicking the updated link. Within the interpreter type

- source('standalone.R')

and the GUI should open.

4.2 Getting Wind Data

The program needs a wind database to calculate the wind generated power. Appropriate wind data is available after registration at the European Centre for Medium-Range Weather Forecasts (ECMWF). Other wind data in netCDF4 files might be used as well, the required database structure is described in section 4.2.1.

In order to navigate to the download page of ECMWF, open http://www.ecmwf.eu/ and navigate to "Research", "Climate reanalysis" and "ERA Interim". Follow the link "ECMWF Public Datasets web

interface"[17]. If you don't have a login, create one. After logging in, a download page similar to that in Fig. 4.1 should appear.

On the download page:

- Select date: Give a range at "Select a date in the interval" or select individual month at "Select a list of months". Do not download more than five years at once. For testing purposes you could download a month or a year of data (not more!).
- Select time: select all
- Select step: select 0
- Select parameter: select "10 metre U wind component" and "10 metre V wind component"
- Click "Retrieve NetCDF"

This leads to a new webpage with filter settings for the region covered (Area) and the grid resolution (Grid). The standard is global data in 0.75° x 0.75° resolution. If you want to reduce the amount of data to download, it is wise to choose only the area needed for your application. The grid resolution should be appropriate for your application. 1° x 1° is still fine for most applications. Read the note below before clicking on "Retrieve now".

Important Note: Even if you do want to download a global dataset and make calculations for routes going from westward of 0°E/W to eastward of 0°E/W you need to set the area on "Custom" and "W" to -180 and "E" to 180.

Now you are guided to a page with the database request to the data server (MARS) and the status of the data retrieval. You have to wait until the retrieval is finished at the server. After that a download Link appears giving the size of the data file (see Fig. 4.2). In the example shown in Figure 4.1 the downloadable data file is 5.3 MB. Depending on grid resolution, the chosen area, the time steps and time span it may take some time to retrieve the data at the server (10 seconds, 10 minutes, even more) before the download button appears. The download file is to be placed in the WIND folder.

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[17] currently the download page is located at http://apps.ecmwf.int/datasets/data/interim-full-daily/

Fig. 4.1: : ECMWF download page for ERA Interim data.

4.2.1   Using your own wind data

The wind data needs to be provided in netCDF format on a regular lon-lat-grid (Gaussian grid). The input file needs to have at least three dimensions (longitude, latitude and time) and five variables (longitude, latitude, time, u10, v10). The conventions are the variables are given in Table 4.1.

Dimension and variable names: The dimensions and variables should be named according to the names in the first paragraph of this section. Advanced users are invited to change the names in the R programme. Variables, which are named according to the format (d|v)Name(Lon|Lat|Time|U10m|V10m) (e.g. dNameLat for the latitude dimension name and vNameU10m for the variable name of the 10 m wind U-component), are set in the beginning of the standalone.R script for setting dimension and variable names.

Variable Name	Name	Description
longitude	Longitude	unit: degree; First lon should be westward of the most westerly waypoint and last lon should be eastward of the most easterly waypoint*
latitude	Latitude	unit: degree
time	Time	Should be in the format "[UNIT] since [YYYY-MM-DD] [HH:MM:SS.S]"**
u10	10 m Wind U-component	unit: m/s; scale_factor and add_offset attributes are allowed
v10	10 m Wind V-component	unit: m/s; scale_factor and add_offset attributes are allowed

* Do not use data going from 0°E to 360°E for waypoints going from 2°W to 5°E but convert data to -180°E to +180°E first.

** e.g. "hours since 1900-01-01 00:00:0.0"

Table 4.1: Conventions for variables in the netCDF which contains wind data.
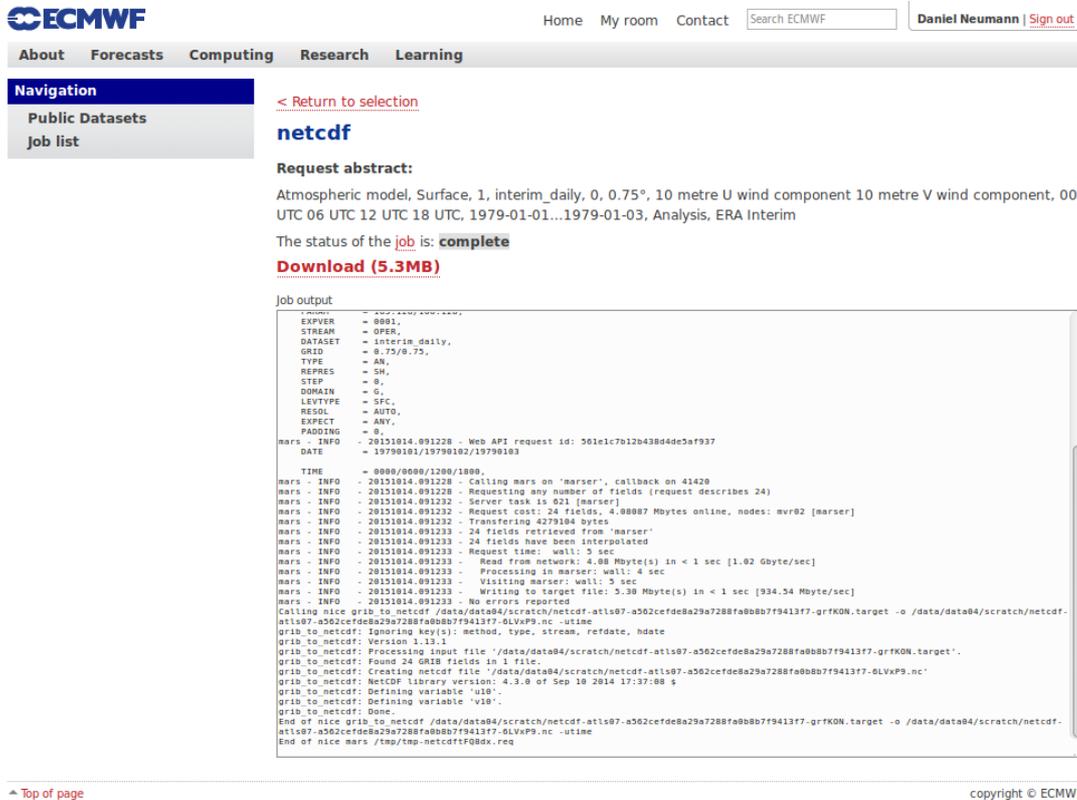
Fig. 4.2: Webpage which shows the status of the data retrieval and of the download. Status of the job can be "queue", "active" or "complete". The download is available when the job status is complete.

4.3 Getting started with wind potentials

The easiest way to understand the program is probably to run a few test cases. Start the programme as described in the installation sections.

Fig. 4.4 shows the GUI immediately after startup. The parameters are set in the middle pane. A predefined file with route data can be chosen with drop-down menu. In a similar way an appropriate wind database is loaded. This may take a few seconds depending on the size of the database. A polar data file for the given sail configuration has to be selected from the list. It possible to add own files with routes and polar data, how to do this and the file format are explained in section 4.5. As mentioned above the program assumes a constant speed, this speed is set in the entry box. Finally, enter the start of the first voyage, the time between two voyages and the number of voyages. In Fig 4.5 all settings are done. Pressing the start button starts the program. In Fig 4.6 the run is finished and the results are shown. The average power per square meter sail and the power generated for 3000 m^2 are displayed. By clicking into the table of results a particular voyage is selected. On the map the wind directions and the wind speed at the time of passing a midpoint are indicated by an arrow. The generated power is encoded as colour. Clicking on a waypoint gives additional information: the

power/m^2 is shown on the map and in the middle pane the course of the ship, the vectors for wind (blue arrow) and ship velocity (red arrow) are displayed in the fixed coordinate system. The grey arrows indicate the apparent wind as seen from the ship based coordinate system. The apparent wind angle is shown in as a green pie slice. The display reflects the complexity of the vector definitions, the wind direction is the direction where the wind comes from, all other vectors point to where the flow or the ship go to. While the program has the keyboard focus and the mouse is inside the map, the left and right key change the selected midpoint, the up and down keys the selected voyage. There is an additional rose plot with the apparent wind angle statistics in a separate window.

4.4   Physical and Mathematical Background

In this section the basic principles on how to calculate the power transferred from the wind on a ship and on how to calculate the apparent wind which is the wind relative to an observed on a ship are introduced.

The first step in estimating power is to calculate the force exerted by the sails onto the vessel. The thrust force F_X and the lateral force F_Y as defined in Fig. 4.3 are calculated by

$$F_X = \frac{1}{2} \, \rho \, A \, c_X(awa) \, v_{rel}^2$$

$$F_Y = \frac{1}{2} \, \rho \, A \, c_Y(awa) \, v_{rel}^2$$

Here ρ is the density of the air, A is the area of the sail, v_{rel} is the apparent wind speed. The coefficients c_X and c_Y describe performance of the sail, they depend on the apparent wind angle awa. The program uses tabulated values for $c_X(awa)$ and $c_Y(awa)$. The lateral force creates leeward drift and is neglected in the current version of the program.
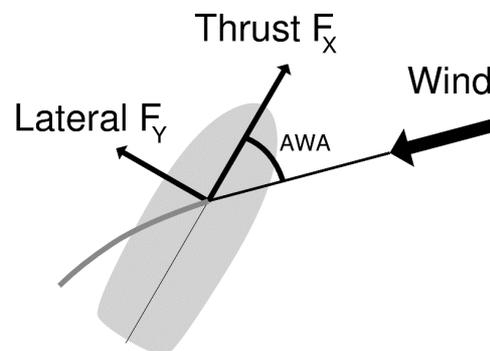

Fig. 4.3: Definition of Thrust F_X and lateral force F_Y as components of the force in the ship based coordinate system. AWA is the apparent wind angle, that is the angle between midship line and the direction of the apparent wind.
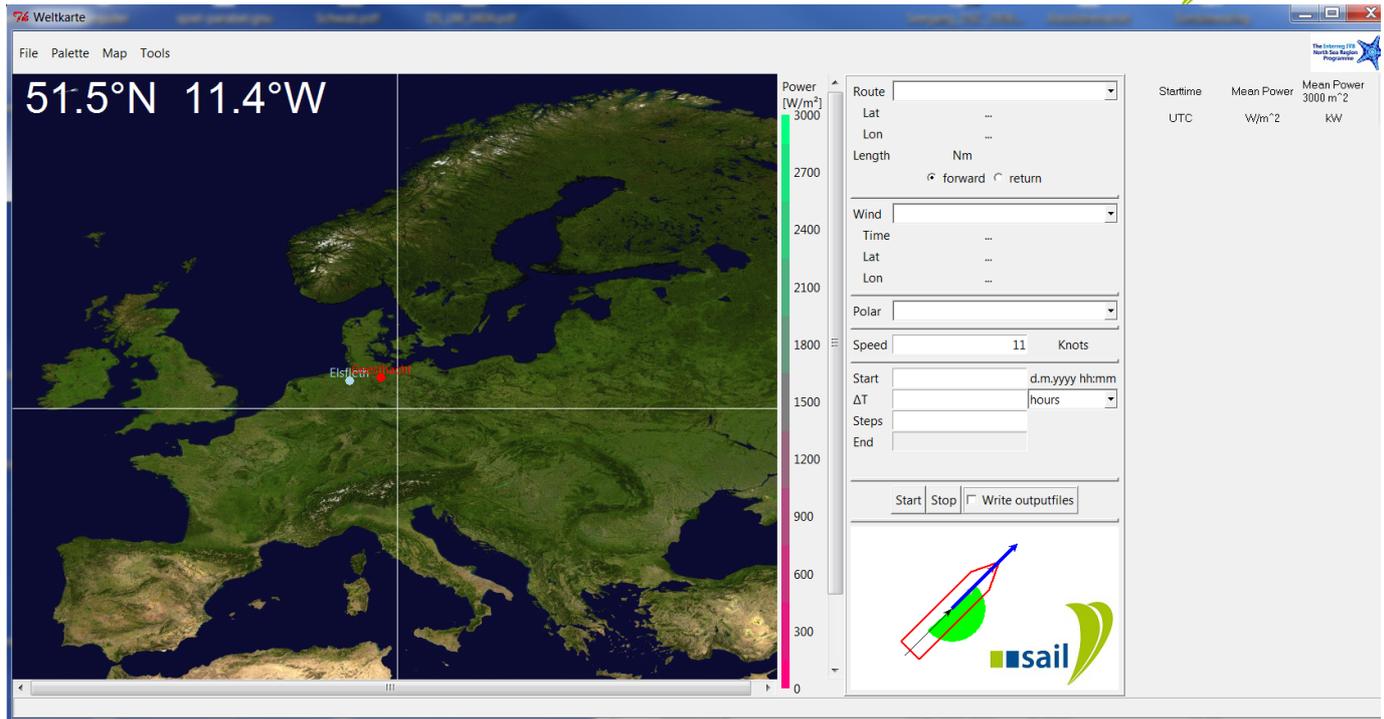
Fig. 4.4: The GUI directly after starting the program. Now the parameters are to be entered in the middle pane.
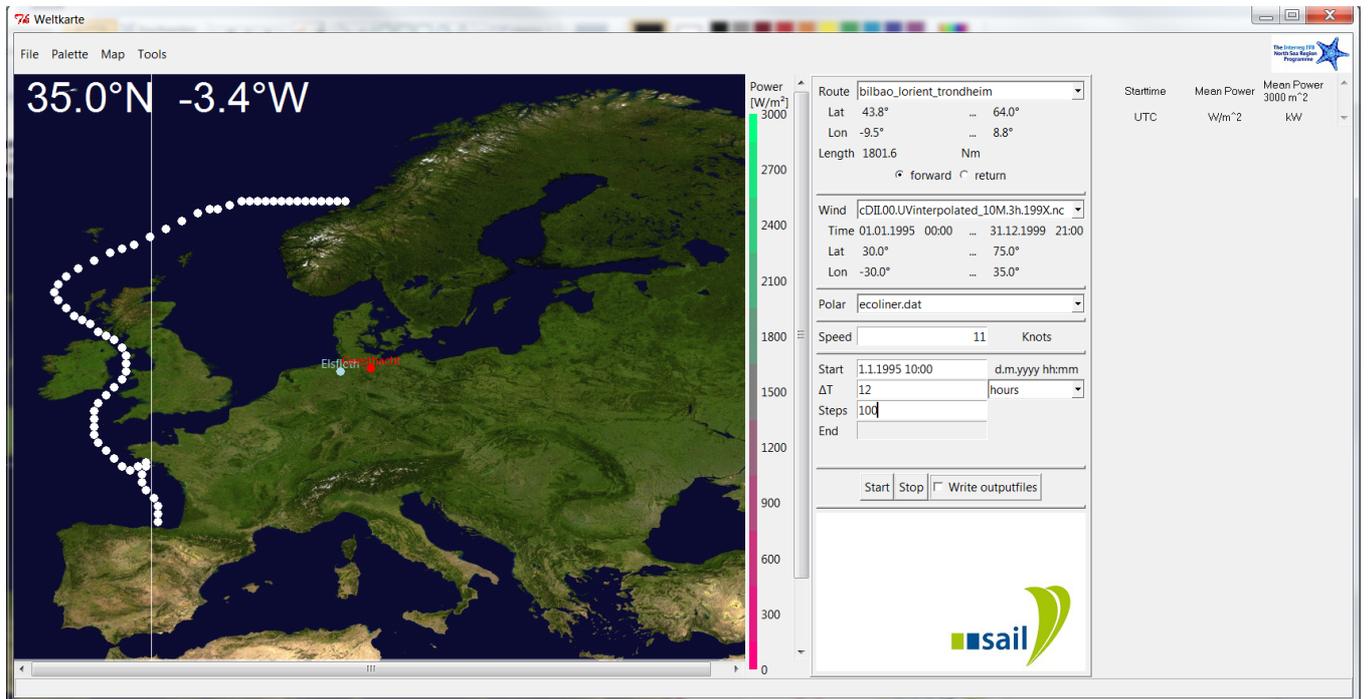

Fig. 4.5: A route is chosen and displayed on the map, a wind data base selected. The polar data for Dynarig on the Ecoliner is used. The first simulation starts at 1.1.1995 at 10:00, there will be 100 voyages in 12 h interval. Press start now.
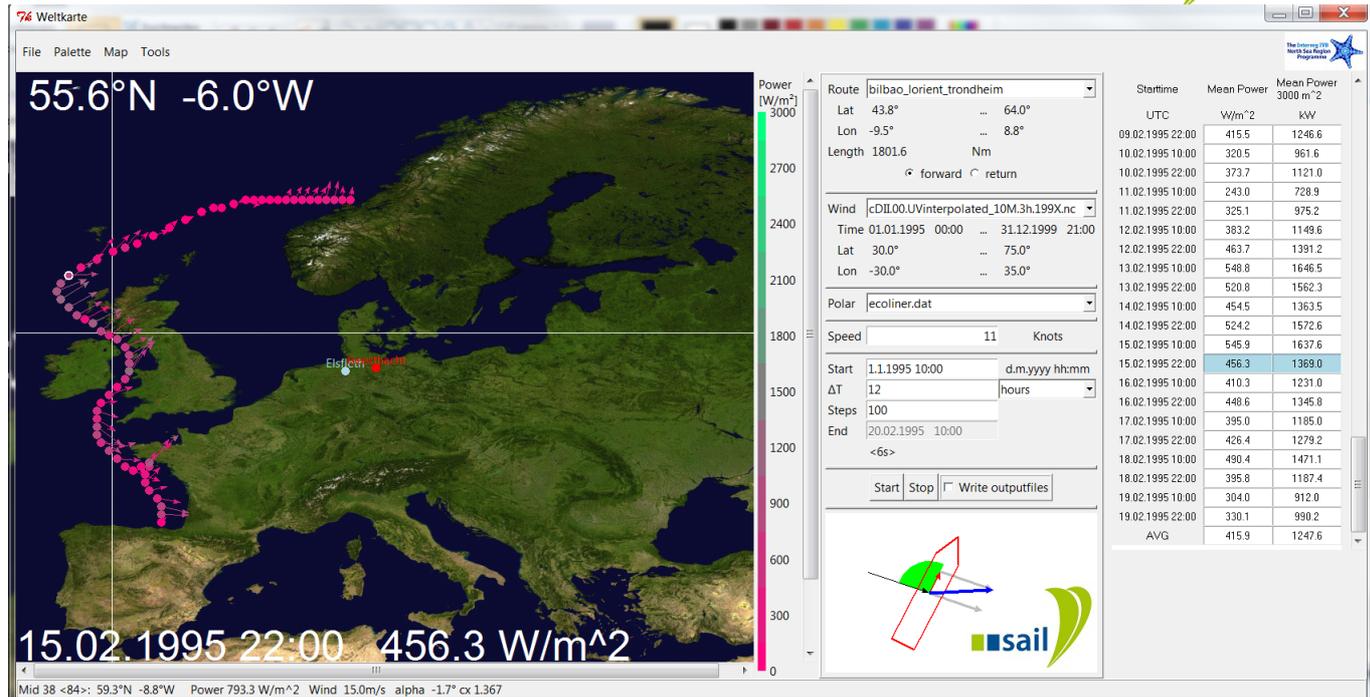
Fig. 4.6: The run is finished after 6 seconds. The mean power for each voyage is shown in the table on the left. Wind speed and direction are shown as arrows on the map at the midpoint of each segment. The color indicates the power generated at the midpoint. While the mouse is in the map area, the arrow keys allow to select waypoints and voyages.

The path travelled by the ship is entered by a set of waypoints. Between the waypoints segments of constant course are placed, constant wind conditions are assumed on each segment. At each midpoint between two waypoints a local Cartesian coordinate system (u, v) with the u-axis pointing to East and the v axis pointing to North is introduced. This coordinate system is used to calculate the segment length, and the u- and v–components of the vessel's velocity within the segment. Next u- and v–components of the wind velocity at the segment midpoint for the time of arrival is looked up in a database. Actually the wind database contains wind velocities on a grid, the program does not interpolate between grid points but takes the data from the grid point closest to the segment midpoint. The difference between the velocity vectors gives the apparent wind. The magnitude of the apparent wind vector v_{rel} enters directly into the force equations. The angle of the apparent wind has to be rotated into the ship coordinate system to give the apparent wind angle α.

The power P_W generated by the propelling force is given by

$$P_W = F_X \cdot v_{ship}$$

here v_{ship} is the speed of the vessel with respect to ground. It might be surprising at a first glance that the power generated by the sail increases with ship speed, doubling ship speed – by for instance use of the engine – doubles the value of P_w for constant F_X. However, the work W_W delivered by the sails for a fixed distance does not depend on v_{ship} as can be seen by integrating the power equation

$$W_W = \int P_W \, dt = \int F_X \, v_{ship} \, dt = \int F_X \frac{ds}{dt} \, dt = \int F_X \, ds$$

here s denotes the arc length of the curve. Thus, the energy gain does not depend on the ship's speed but the power does. The work delivered on a segment is given by the equation above, the total work is just the sum over all segments. The mean power is given by the ratio of total work divided by total travelling time.

As noted above many aspects are neglected in this program which are taken into account in the commercial voyage simulation tools. The program does not consider depowering techniques like reefing or sheeting in strong winds. It does not optimize route or ship speed for better wind conditions. Route optimization could be important for journeys on the oceans, such as from Spain to the Caribbean. However, in the North and Baltic Sea regions spatial constraints such as the traffic separation scheme limit the options for optimization. The power estimates are compared against detailed travel simulations. The results showed that estimates of a professional voyage simulation tool and of this programme are in the same order of magnitude when comparing monthly or annual averaged power savings.

4.5   Input and output files

The programme uses a netCDF interface to read the wind database. For the examples shown below wind data for the years 1990 to 2010 were taken from the coastDatII[18] data set. The wind data are part of a hindcast from 1948 to today calculated by COSMO-CLM[19]. These data can be obtained via the CERA database[20] as described in section 4.2. Wind input data is placed in the WIND sub-directory.

The wind propulsion system is described by a text file with three columns. The first column is the apparent wind angle in the range from zero (wind from the bow) to 180° (wind from the aft). The second column is the coefficient c_X. The third column is not used but introduced for compatibility with other programs and has to be specified. The program does a linear interpolation of $c_X(\alpha)$ between the tabulated values. These files are to be placed in the sub-directory POLAR.

Waypoints are given in a text file with longitude in the first and latitude in the second column. Both values are given as float numbers in degrees. The waypoint files are to be place in the sub-directory ROUTE. These files are also denoted as "route files".

Additional output files for deeper analysis are written if the box is checked. These files are found in the sub-directory OUTDATA. Three files are created in a run

- <route>_averaged.dat contains comma-separated values. The first line is a headline, the second line contains the power/m^2 averaged over all voyages of one run. The first column is a label, the second column is the average over all midpoints, the columns give the average power for the individual midpoints. The third and fourth line contains the coordinates of the waypoints: a bug that is going to be fixed.
- <route>_detailed.dat contains comma-separated values. The first line is a headline, the following lines give information on the individual voyages. The first and second column contain

---

the departure time and the power/m^2 averaged over all segments, the following columns are the power/m^2 for individual midpoints.

- <route>_trip.dat has trip start time and averaged power/m^2 for the total trip. The first line is a headline.

In the filenames above <route> denotes the name of the route file. The output files are overwritten by another run of the program with writing of output enabled.

5 Propulsion catalogue

This section provides a list of commonly used wind propulsion devices. The tables 5.1 and 5.3 give an overview of the system and the source of the data. Detailed data in terms of lift- and drag or thrust and lateral force coefficients are given in the appendix. What do these coefficients mean? Consider a lifting device like wing or a sail placed in flow (Fig. 5.1). In this case the flow exerts a force onto the device. The component in the direction of the flow is called drag F_D, the normal component is called lift F_L. In the simplest approximation these forces are given by

$$F_L = \frac{1}{2} \rho A c_L(\alpha) v^2$$

$$F_D = \frac{1}{2} \rho A C_D(\alpha) v^2$$

Here ρ is the density of the fluid, A is the sail area, v is the speed of the flow. The device is described by the dimensionless coefficients for lift c_L and drag c_D. Both coefficients depend on the angle of attack α. The values for c_L and c_D are determined in wind tunnel experiments or CFD calculations.
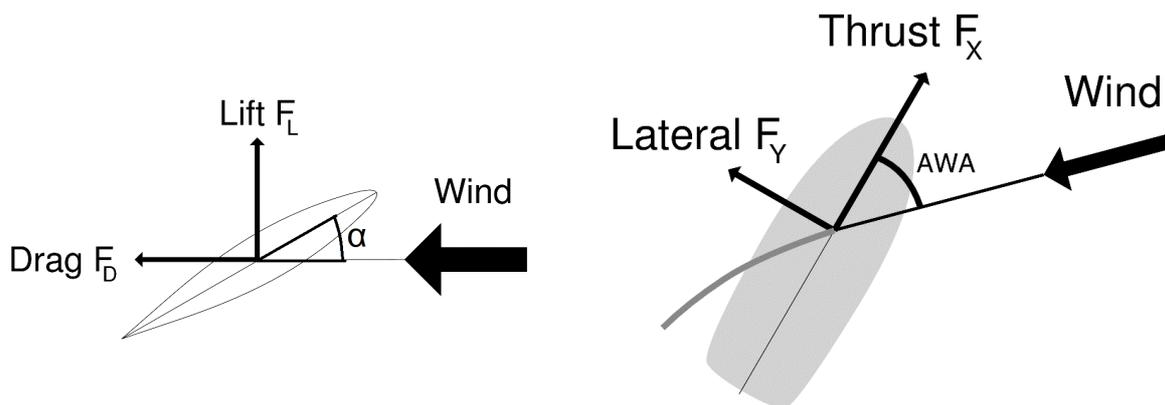

Fig. 5.1: Left panel: lift and drag forces are defined relative to the incoming flow. Right panel: thrust and the lateral force are defined with respect to the ship hull.

In the right panel of Fig 5.1 the sail is placed on a ship, this defines the apparent wind angle AWA. Given this angle components for thrust F_X and lateral force F_Y are calculated from the above formulas. Usually the coefficients c_X and c_y are introduced by

$$F_X = \frac{1}{2} \rho A c_X(\alpha) v^2$$

$$F_Y = \frac{1}{2} \rho A c_Y(\alpha) v^2$$

These coefficients are for instance used by the wind potential program of section 4. The values given for these coefficients in the appendix are first approximations useful for rough estimates. For detailed

studies the values for c_x and c_Y for the actual configuration and superstructure have to be determined. This can be done wind tunnel tests (section 7) or CFD-calculations.

How to choose a propulsion system? The wind potential program (section 4) tells something about the possibly generated power. Detailed voyage simulations (section 9) produce rather exact figures on fuel consumption and fuel savings. But the decision on a certain propulsion system includes other factors like "usability" that cannot be expressed in numbers. How to identify the important parameters and how to rate them? The work package designed a score matrix (table 5.1) with the factors considered important. Next everybody was asked to rate each propulsion system in the score matrix and document the reasons for his decision. The results were averaged and discussed on a meeting. So the score matrix is shown in table 5.4. Please note that the individual scores depend on the given design target, they are not of general importance. The import part is the outline of the score matrix: it is a tool to facilitate the decision on wind propulsion systems in early design stages. The scores seen here are subjective. They are an indication only.

5.1 Literature

Clauss, 2007: Clauss, Siekmann, Tampier: Simulation of the Operation of Wind-Assisted Cargo Ships. 102. Hauptversammlung der Schiffbautechnischen Gesellschaft in Berlin, 2007

Schenzle, 1985: Schenzle: Estimation of wind assistance potential, in Satchwell (ed.): Windship Technology, Proceedings of the WINDTECH '85), 1985

Graf, 2013: Graf, Rentzsch: Neuartiger Segelantrieb als Hilfsantrieb für Megayachten und Handelsschiffe, Schiff und Hafen, 2, 2013

Traut, 2014: Traut, Gilbert, Walsh, Bows, Filippone, Stansby, Wood: Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes, Applied Energy, 2014

Smulders, 1985: Smulers: Exposition of calculation methods to analyse wind propulsion on cargo ships, in Satchwell (ed.): Windship Technology, Proceedings of the WINDTECH '85), 1985

Bergeson & Greenwald, 1985: Sail assist developments 1979-1984, in Satchwell (ed.): Windship Technology, Proceedings of the WINDTECH '85), 1985

Charrier, Constans, Cousteau, Abdallah, Malavard, & Quinio, 1985: The foundation Costeau and windship propulsion 1980-1985, in Satchwell (ed.): Windship Technology, Proceedings of the WINDTECH '85), 1985

Traditional gaffel rig	Bermuda mainsail	Traditional square rig	Dyna rig	Rigid square rig
A traditional gaffel rig is recognizable by the angle between the spar and the mast. The main sail is connected to the spar, the mast and the boom.	The mainsail of a Bermuda rig is triangle shaped and connected to the mast and the boom.	Sails are carried on horizontal spars. Characteristic to the traditional square rig is the possibility for the horizontal spars to swing around the fixed mast.	The DynaRig is a modern version of a square-rigger. The horizontals spars are fixed to the mast. The whole mast is rotated to engage the wind angles.	
Schenzle, 1985	Schenzle, 1985	Schenzle, 1985	see section 7	Schenzle, 1985?
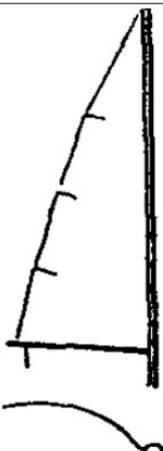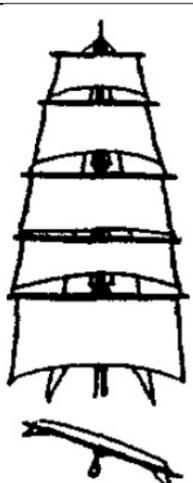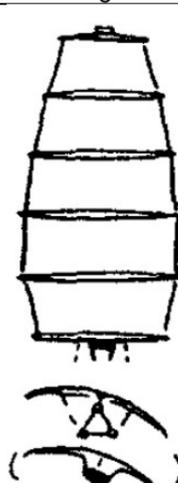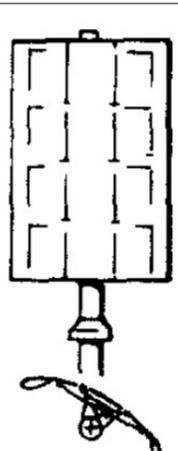
Table 5.1: Propulsion catalogue.

Autares	Kite sail	Wing sail	Multi Wing sail
A twin sail arrangement set on a mast with upper and lower turnstile. The setting of the sail is controlled by rotating the mast or moving the sails along the arms of the turnstile.	A kite, connected to the ship with a high strength synthetic fiber, pulls the ship forward. Steering the kite, with a control pad into dynamic flight manoeuvres in the air, generates tractice force to the ship.	A fixed sail structure build up with a airfoil as cross-section	Structure with multple wingsails
Graf, 2013	Traut, 2014	Smulders, 1985	Clauss, 2007?
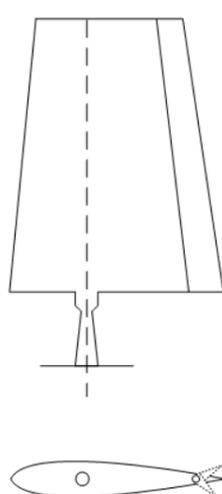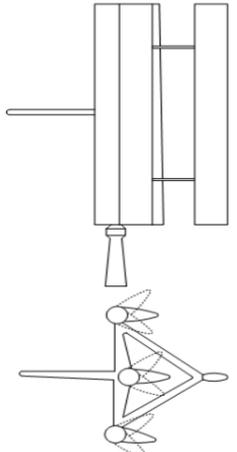
Table 5.2: Propulsion catalogue continued.

Flettnerrotor	Turbo Sail	Horizontal as wind turbine (HAWT)	Vertical as wind turbine (VAWT)
A rotating cylinder in airflow creates forward energy by means of the Magnus effect.	A ovoid shaped tube with a mobile flap which creates forward energy by means of the Magnus effect.	The axis of this type of wind turbine is horizontally orientated. The variants are; one – to fore bladed wind turbine, energy ball, Savonius-rotor and venture- wind turbine.	The axis of this type of wind turbine is vertical orientated. The variants are; Savonius, Darrieus, Aerotecture, Giromill, Cycloturbine, Quietrevolution wind turbine, Turby, windwokkel,
Bergeson & Greenwald, 1985	Charrier, Constans, Cousteau, Abdallah, Malavard, & Quinio, 1985		

Table 5.3: Propulsion catalogue continued.

		Soft Sails					Rigid Sails		Mechanical Sails		Turbines				
	Weight Factor	Gaffel Rig	Bermuda Mainsail	Square Rig	Dyna-rig sails	Kites	Wing sails	Mulit Wing sails	Flettner Rotors	Turbo sails	HAWT	VAWT	Windmill	Landmiller	Power planes
1 Cost	2	4	4	4	2	3	3	2	2	2	3	3	3	1	3
2 Performance	3	3	4	2	4	3	4	3	3	3	4	4	4	2	2
3 Uptime/Downtime with respect to winddirection	1	3	3	3	3	3	3	3	4	4	5	5	5	3	3
4 Ease of use / Operability	2	2	3	2	5	3	5	4	5	5	4	4	4	1	4
5 Place taken on the deck (ease of loading/unloading, sight lines)	3	1	1	2	3	5	4	3	4	4	2	2	2	4	4
6 Weight/volume of system	3	5	4	4	4	5	3	3	3	3	4	4	4	3	3
7 Automation opportunities	2	1	2	2	4	4	5	5	5	5	4	4	4	2	3
8 Robustness	2	3	3	3	4	4	4	4	4	4	3	3	3	1	3
9 Wind load (in case of weak or strong winds)	2	4	4	3	4	4	2	2	3	3	2	2	2	4	3
# Impact on stability (heeling moment; 1=lot of moment;5=no mo	1	2	2	2	3	4	3	3	5	5	5	5	4	3	4
# Technological Maturedness	2	5	5	5	5	4	3	3	2	2	1	1	2	1	1
Total		70	74	67	87	90	83	73	81	81	74	74	75	53	68

* The weighing factor is to be chosen in a range of 1 to 3.
You give the weighing fac tor of 3 when you believe that this specific criteria is very important for the selection of the WASP.

** Give a number from 1 to 5 to what you believe is a strong point of a certain WASP.
The number 5 means you believe it the specific WASP scores really good on that criteria.
The number 1 means you believe the specific WASP does not score on that criteria

Your input will be collected and weighed.
In order to have a fruitfull discussion it is important to write a motivation for your scores you have indicated above in a separate document.
The average score will be the basis on which we will chose the 3 WASP's with the most potential.
Of course the choices are than still open for discussion. The final choice will be made in a meeting.
Please note that indicating your motivation clearly helps in convincing others. So please do this!!!

Table 5.4: The score matrix for WASP devices.

6   Conceptual design: the Flettner Freighter

The Flettner freighter is a concept that combines several features that focus on future shipping, the hull form, Wind Assisted Ship Propulsion (WASP) and a main engine running on LNG.

The concept is a general cargo ship which allows better use of the cargo hold and could add different loading configurations on the deck. However to ensure a better wind flow to the rotors the height of the cargo on the deck should be limited.

The hull form of the Flettner freighter WASP hybrid concept differs from a conventional design in such a way that the hull characteristics are better suited for drift and heel situations. The hull form result is based on a financial analysis of multiple options. The best hull form coefficients are the ones that go with the best financial results. The financial results include the operational, constructional costs as well as the total ROI. As a result the most ideal proportions of the hybrid design in comparison to a conventional design (at a DWT of 7600t) should be as seen in table 6.1.

	Conventional	WASP Hybrid
L_{OA}/B [-]	7.35	6.76
B/T [-]	2.31	2.94
D/T [-]	1.39	1.38

Table 6.1: Proportions of a conventional design and a WASP Hybrid design at equal DWT

Because of the added resistance due to leeway, the hull resistance in upright condition in comparison to that with a conventional design should be reduced in order to maintain an equal amount of total resistance. This is done by creating a sharp entrance of the water on the bow. This sharp angle continuous up to over halve length of the hull form resulting in a hull form similar to that of a sail ship. This reduces the added wetted surface under heel, in comparison to upright condition.

The hull form slenderness results in a lower steel weight-to-volume ratio in comparison to that of a conventional design, as seen in table 6.2.

	Hybrid Concept Design
Steel weight-to-Volume [-]	16% decrease

Table 6.2: Steel-to-Volume decrease in percentage in comparison to a conventional design at equal deadweight

Still, the beam of the design does increase in order to counter the added WASP forces that result in constant heel of the ship.

The deckhouse has been placed at the bow to ensure better visibility from the bridge in contrast to the location aft of the Flettner rotors. Due to the slenderness of the underwater body, especially in the forward part, the deckhouse location also contributes to a better weight distribution.

Figure 6.1: 3D-render of the Flettner Freighter Concept

The Flettner freighter is a concept that uses a main engine complimented with Flettner rotors to propel herself. The Flettner rotor uses the Magnus-effect to convert wind energy into thrust. This happens through influence of the boundary layer of the wind flow around the Flettner rotor. Therefore the rotors are to be powered in order to spin around its axis. This is done by using separate generators fueled by either LNG or MDO.

A specific feature of the concept is the inclusion of movable aft rotors. This helps to find the balance between the center of effort of the WASPs and the center of effort of the underwater body and thus limiting the amount of drift. Both rotors are located on a movable car that can be moved over the full length of the cargo hold. The movable car is at the same time the hatch crane. This movable option can only be used when there is no cargo on the deck. The position of the Flettner rotors or the clear range of the track can be determined prior to the journey. Eventually the position of the aft Flettner rotors can be fixated if the cargo type and trade route are known.

The costs of a WASP hybrid design in comparison to a conventional design have been estimated and show the estimations as seen in table 6.3. This is due to the installation of the WASPs of which the costs are likely to reduce when the technology matures. Also the slender design of the hull results in additional labor costs due to a more difficult construction.

	Hybrid Concept Design
Building Costs [$]	28% increase

Table 6.3: Building cost results of the hybrid concept in comparison to the conventional design at equal deadweight

The power saving potential of the Flettner Freighter concept design when sailing 13 kts with four rotors of 3.7 x 20 meters with a max of 300 rpm can be seen in Fig. 6.2. For this impression the net power reduction as a percentage of the theoretical upright resistance power $P\phi0$ is assumed to be a measure for the fuel consumption as a percentage of the normal fuel consumption if no rotors are installed. This is however a comparison based on equal fuel type for the main engine and the Flettner rotors and based on a conventional ship fueled by HFO.

$$\% \, Fuel \, saving = \frac{net P_{red}}{P_{\varphi 0}}$$
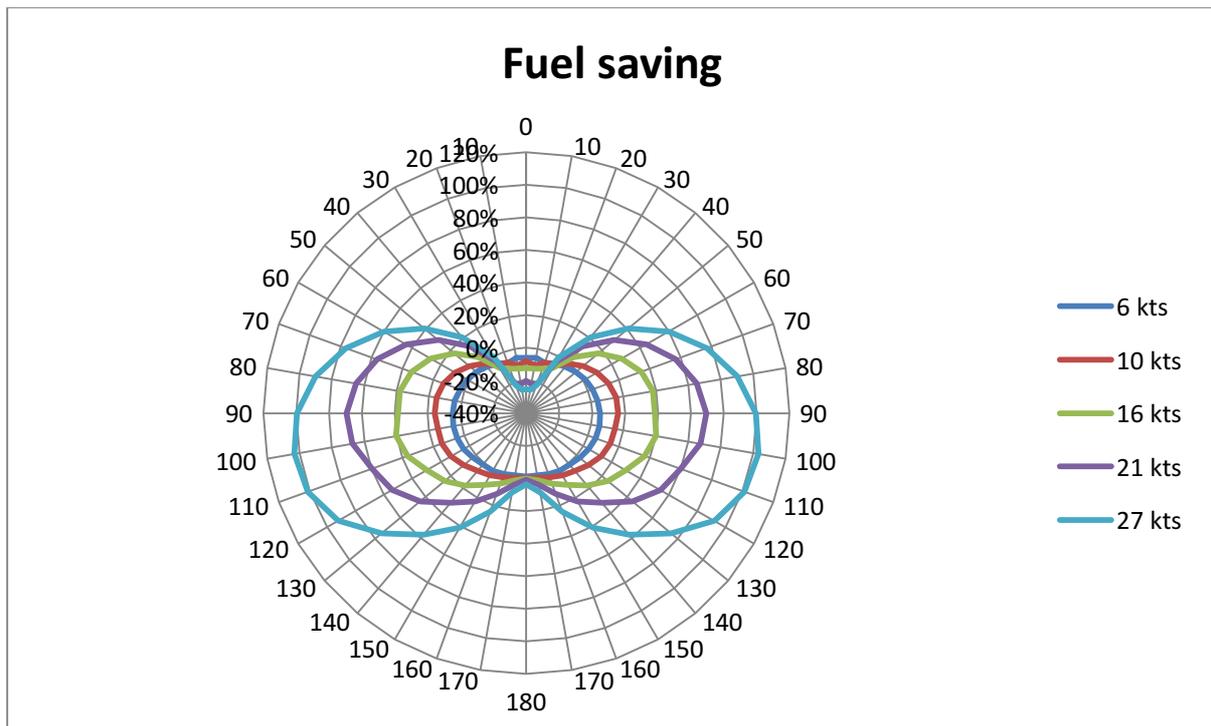
Figure 6.2: Polar diagram of the net power reduction as a percentage of the normal upright resistance without Flettner rotors installed

The power saving average over all headings in 6 Bft wind (27 kts) is about 46%, when considering that all the headings occur for the same time period. The outcomes show that power can be saved on headings between 20 – 180 degrees relative to the wind starting from 2 Bft. The greatest contribution to the ship propulsion is obtained on beam reach headings. The smallest contributions occur on downwind headings and can be negative when the ship is sailing faster than the wind. When sailing upwind the negative contribution is only a fraction of the profit that can be gained on beam reach headings. The optimum rotational speed is different for all headings and wind speeds and should be chosen when a specific route is known.

Roadmap for Sail Transport: Engineering

Our recommendation is to further investigate mechanical losses, electrical losses, propeller efficiency and added resistance due to waves and drift. This should lead to a judgement of viability of this hybrid design.

The summary of all the ships parameters are as follows:

General

Length overall	120,46	m	Air draught (top of Flettner	35,0	M
Length between	117,38	m	Design speed	13,0	Kts
Breadth hull	18,00	m	Deadweight	5000	T
Depth maindeck	9,53	m			
Design draught	6,00	m			

Loading Capacities

Total hold volume	6320	m^3	Area floor hold	445	m^2
Dimensions hold opening	62,3 x	m	Area maindeck hold	747,6	m^2
Height closed hold	16,90	m	Displacement	7956	T

Propulsion & Manoeuvring particulars

Main engine (approx.)	4000	kW	Flettner rotor diameter	3,70	M
Number of Flettner rotors	4	-	Flettner rotor end disc	7,40	M
Flettner rotor height	20,0	m	Rotational speed	300	Rpm
			Required power Flettner	4 x 70	kW

SIDE VIEW

UPPER DECK

TWEEN DECK
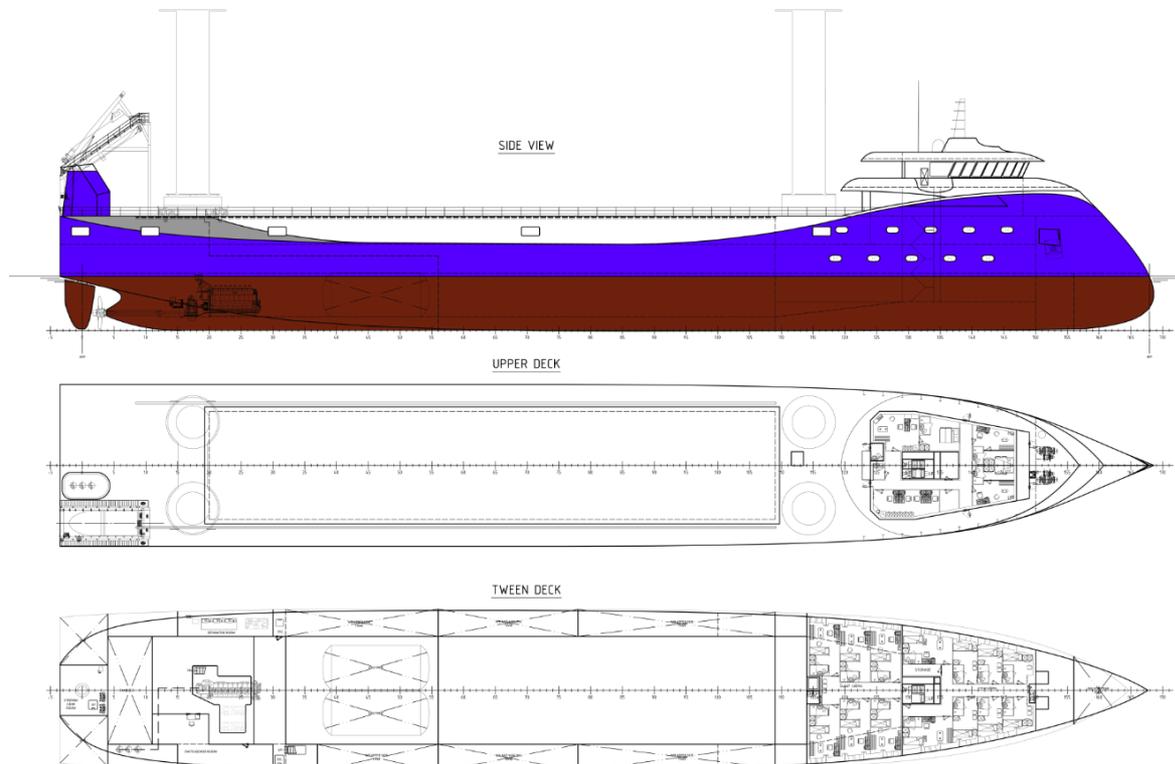
7   Aerodynamic performance: Wind tunnel tests for the Ecoliner

The Ecoliner is a design concept by Dykstra Naval Architects, it features a 8000 DWT multi purpose cargo vessel equipped with three Dynarig masts. In order to evolve this promising design, operational and aerodynamic characteristics were studied in the SAIL project. In this section wind tunnel tests conducted within the SAIL project by the Wolfson Unit, Southampton and coordinated by Dykstra Naval Architects[21,22] are documented. The tests were conducted in two phases:

1. Determine the most appropriate mast configuration. Tests considered only one mast without any ships superstructure
2. Determine the most appropriate configuration of multiple masts onboard. These tests were done with a varying sail area and number of masts.

Dykstra Naval Architects decided that the rig with 3 masts and 1200m^2 of sail area per mast was the most favourable to proceed with. It is believed to be less costly than a 4-mast rig and achieves good performance. Consequentially, this rig was also used to determine the operational performance using voyage simulations as discussed later in this report. Figure 7-1 shows the chosen configuration in the wind tunnel including deck cargo. It was observed that having deck cargo improves performance due to the reduction of vortices at the base of the sails. This is only the case for the vessel with sails set. Otherwise the cargo decreases performance.
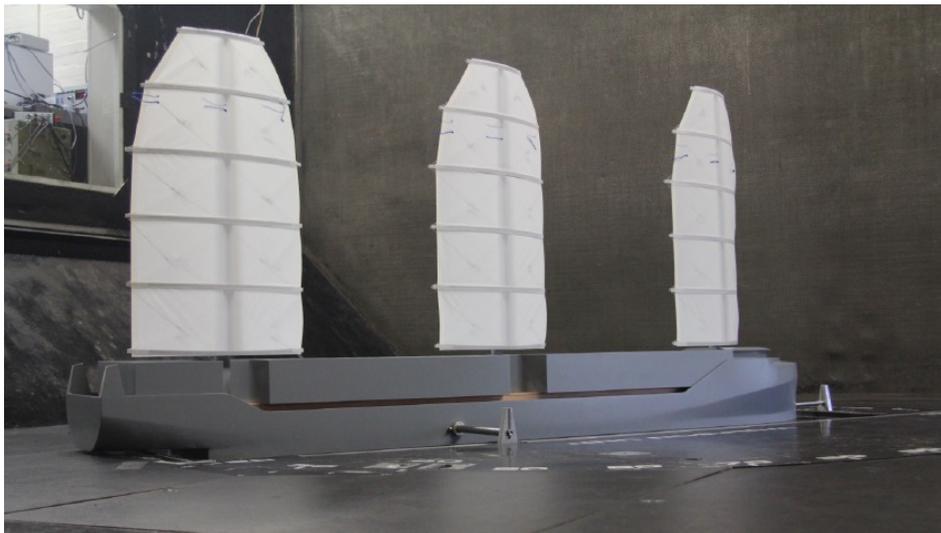
Figure 7-1: Ecoliner in the wind tunnel including cargo

Figure 7-2 shows the lift and drag coefficient for the maximum driving force as determined from the wind tunnel tests for the chosen vessel configuration including cargo. The wind tunnel results also showed the effect of sheeting in and out and reefing.

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[21] "Wind tunnel sail tests on different variations of a Dynarig style concept," Wolfson Unit, Southampton, United Kingdom, 2511, Mar. 2014.

[22] Wind tunnel sail tests on a wind assisted ship 'Ecoliner,'" Wolfson Unit, Southampton, United Kingdom, 2545, Nov. 2014.
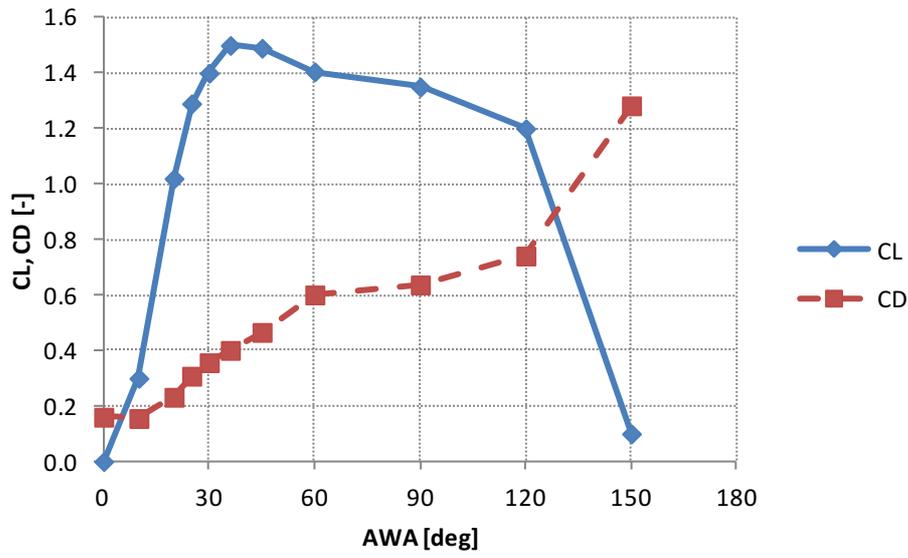
Figure 7-2: Sail force coefficients for maximum driving force

8 Hydrodynamic performance

SAIL project involves sailing prediction of two hull forms. One which is 3000 DWT coaster which is adopted from a conventional coaster hull form. This document describes the hydrodynamic force predictions based on CFD calculations of the hull form in various leeway and heel angles across the speed range. Some results are shown here in graphical from demonstrate the effect of heel and leeway on the performance of the ship[23]

8.1 Hull form and characteristics

The hull form is provided by MARIN in IGES form. Main characteristics of the hull form is given below on Table 8.1.

Variable	Symbol		Unit
Ship Length overall	L_{OA}		m
Ship Length between perpendiculars	L_{BP}		m
Ship Length waterline	L_{WL}	86.942	m
Ship Length wetted	L_{WS}		m
Breadth	B	13.6	m
Draught ap	T_A	4.4	m
Draught midship	T_M	4.4	m
Draught fp	T_F	4.4	m
Displacement Volume	D	4145.8	m3
Displacement	D	4249	ton
Midship section coefficient	C_M	0.989	
Block coefficient	C_B	0.806	
Prismatic coefficient	C_P	0.815	
Waterplane coefficient	C_{WP}	0.906	
Longitudinal center of bouyancy	LCB	42.371	M from AP

Tabelle 8.1: Geometric properties of the 3000 DWT coaster

8.2 CFD Calculations

The IGES hull form supplied by MARIN is utilised in CFD calculations. ANSYS CFX is utilised in the CFD calculations in fixed body form as performance of the ship shall be dependent on the hull form attitude due to wing force generation system.

CFD calculation were performed with 1/20 scaled model with 1.6 million mesh members as demonstrated in Figure 8.1.

5 different speeds are used in the calculations as 5, 6.5, 8, 9.5 and 11 knots of speed. For all the speeds the heel angles of 0, 2.5, 5, 7.5, 10 degrees and leeway angles of 0, 2.5, 5, 7.5, 10 were used. For all the calculations hydrodynamic forces and moments were derived.

The results of the calculations are presented in Ship Scale, without any allowances for the appendices, roughness, air drag etc in 8.3 to 8.12.

A comparison between the CFD predicted resistance and MARIN database predicted resistance is given in Figure 3.2 for comparison. MARIN predicted resistance is slightly higher than CFD as it includes the appendage resistance as well.

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[23] for the complete report see Insel, Olcer: Speed-Resistance-Power prediction for a 3000 DWT coaster in sailing conditions, Report Number Sail.r1, WMU Malmö
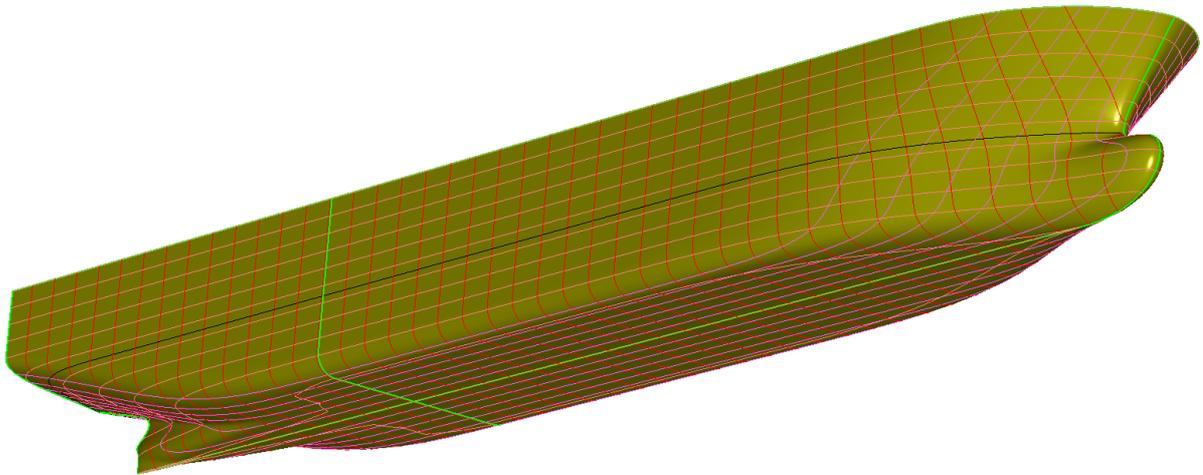
Fig. 8.1: Hull form for 3000 DWT coaster
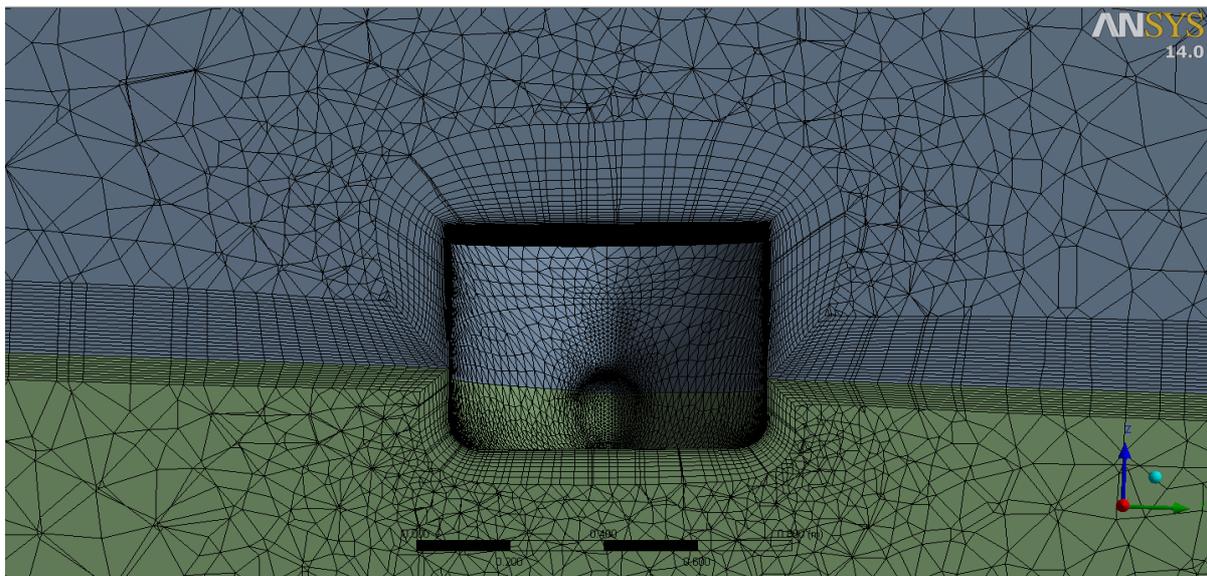
**Figure 8.2 : Mesh utilised in CFD applications.**
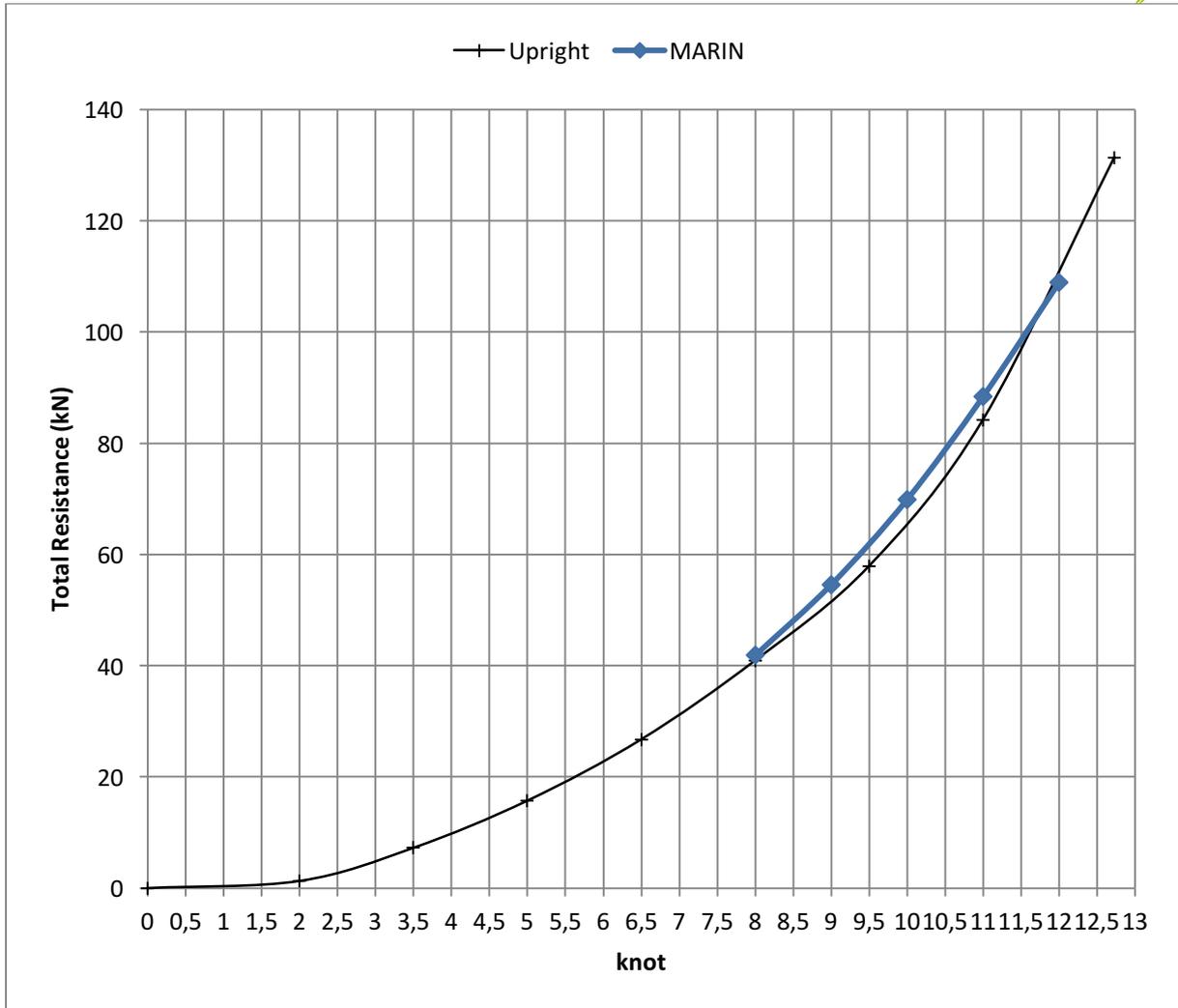
Figure 8.3: 3000 DWT coaster upright total hull resistance for heel angle of 0 degrees and leeway angle of 0 degrees
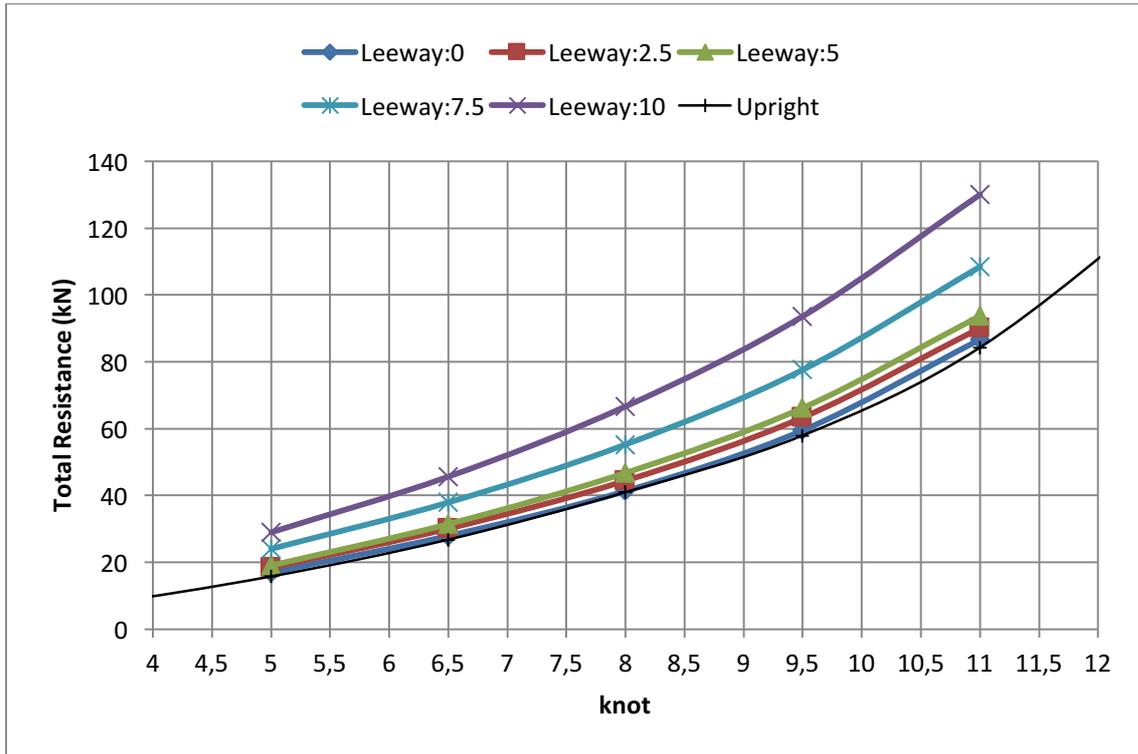
**Figure 8.4: 3000 DWT coaster total hull resistance for heel angle of 0 degrees**
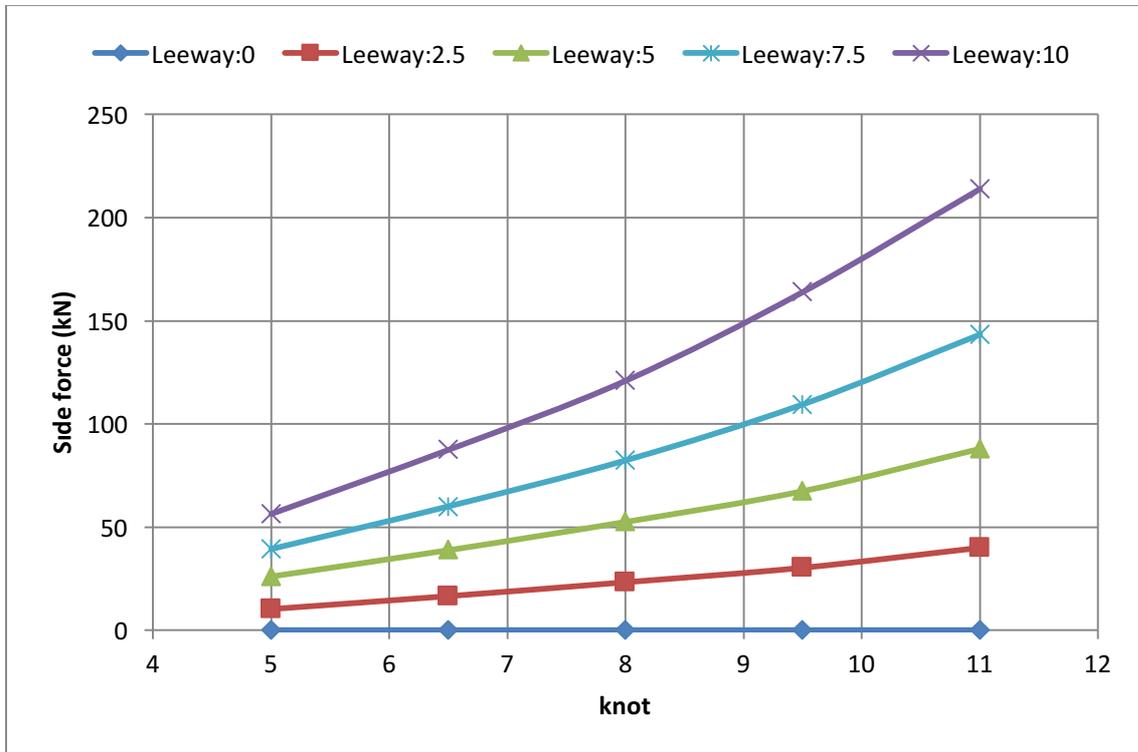
**Figure 8.5: 3000 DWT coaster total side force for heel angle of 0 degrees**
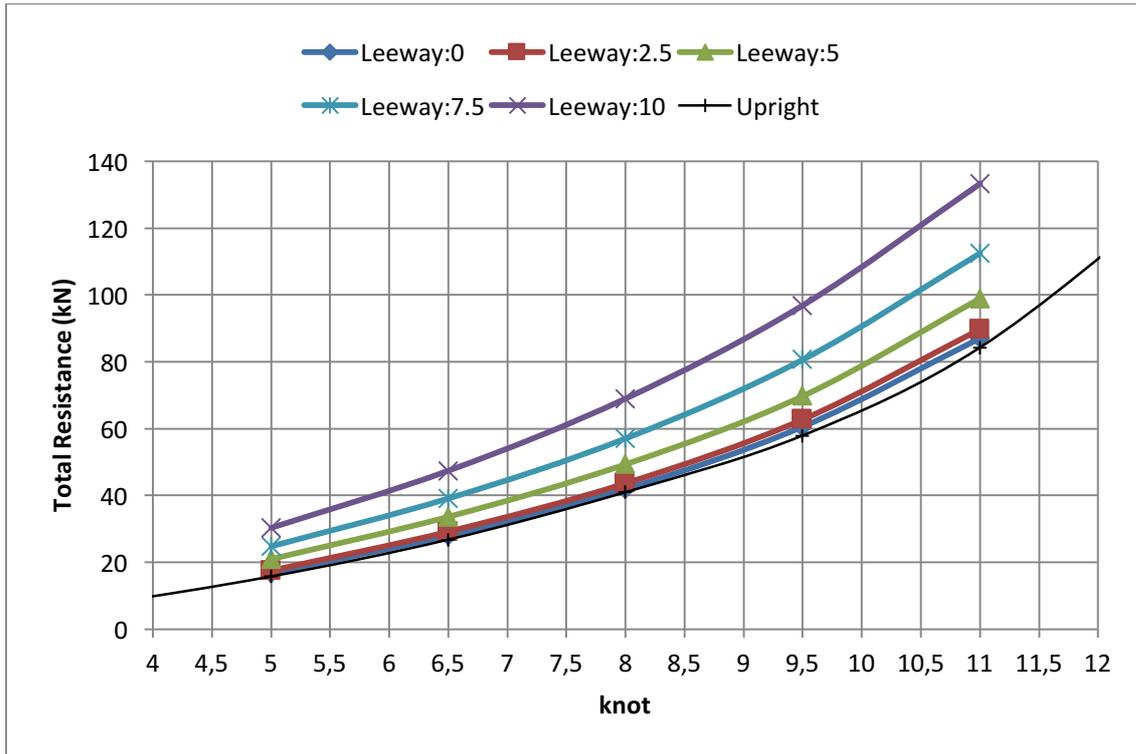
**Figure 8.8: 3000 DWT coaster total hull resistance for heel angle of 5.0 degrees**
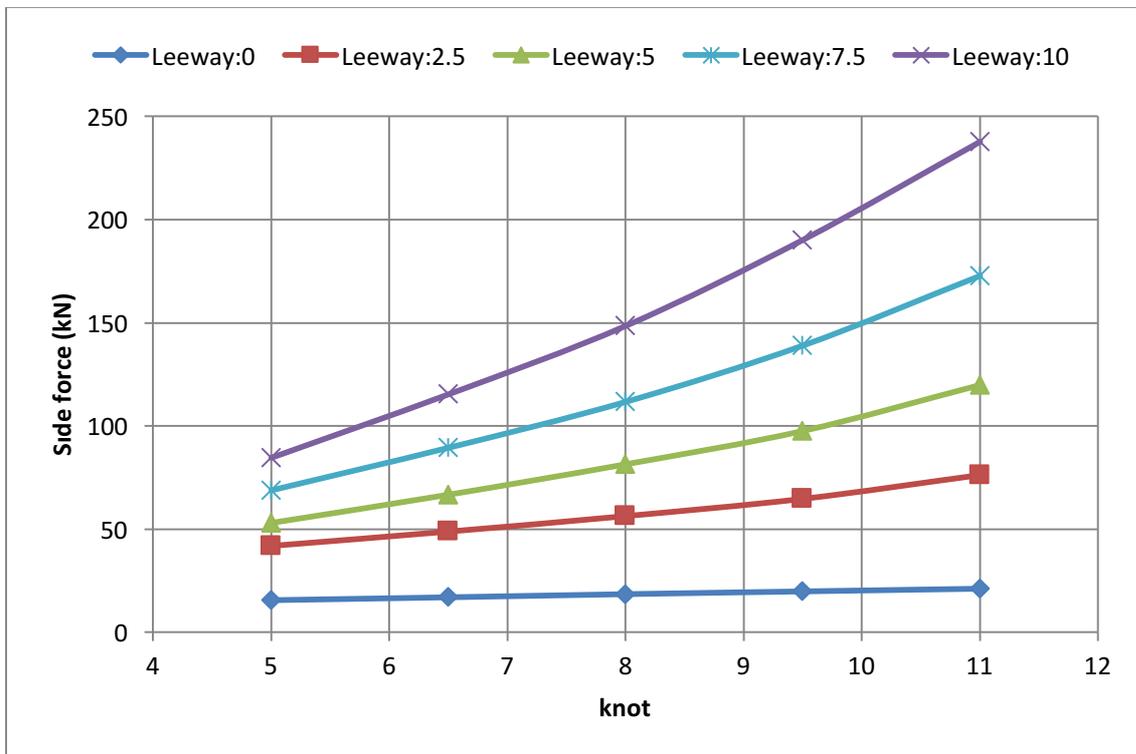
Figure 8.9: 3000 DWT coaster total side force for heel angle of 5.0 degrees
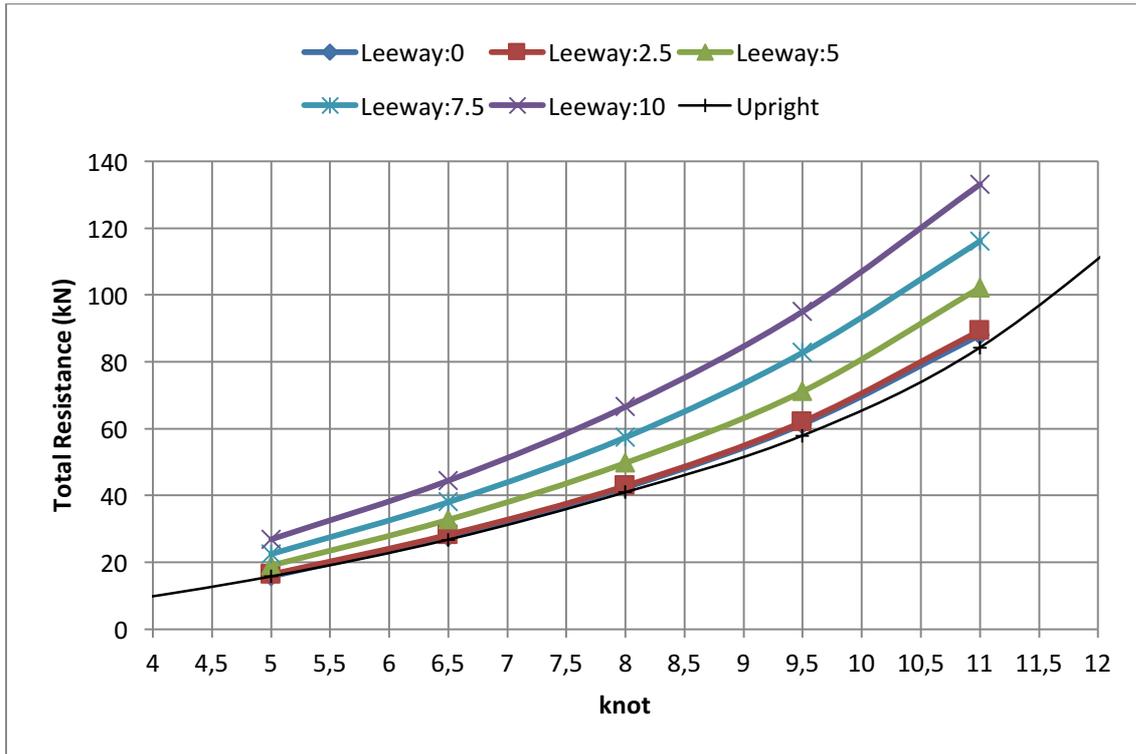
Figure 8.12: 3000 DWT coaster total hull resistance for heel angle of 10.0 degrees
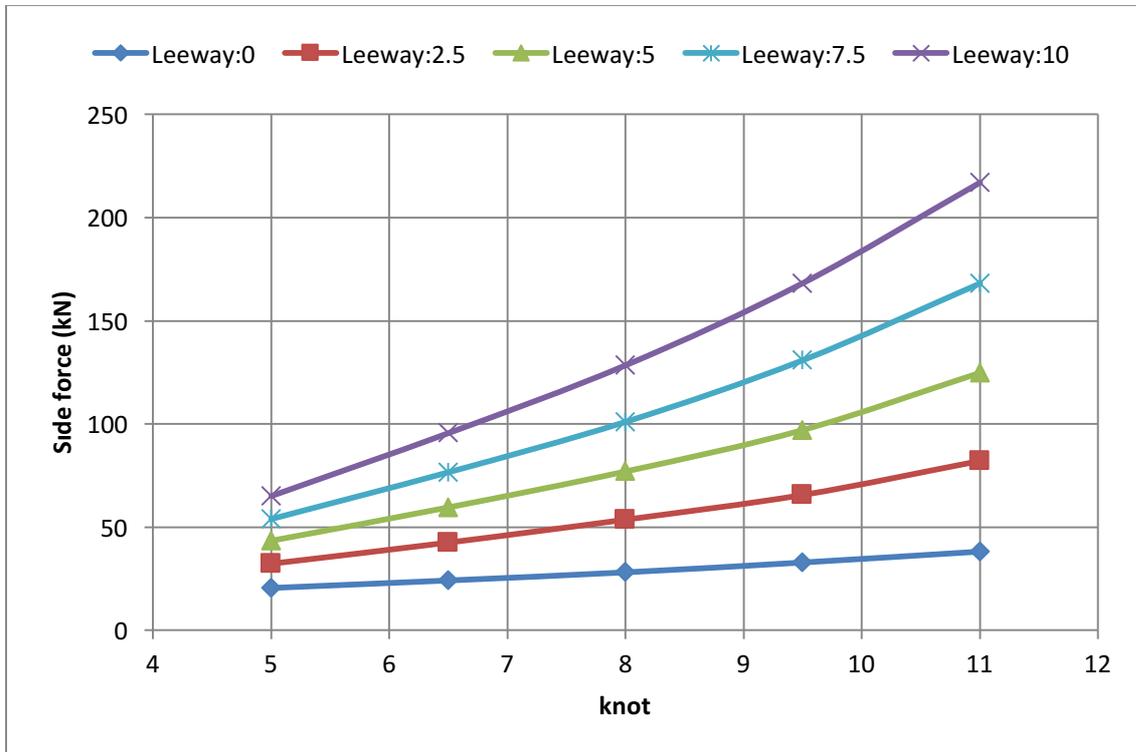
Figure 8.12: 3000 DWT coaster total side force for heel angle of 10.0 degrees

9 Operational performance

As a final step in the evaluation of wind assisted ships, a prediction of the operational performance is made. The intention here is to capture the influence of weather and sea conditions on a particular route and to get to a prediction of average fuel consumption. Such a prediction can be made to various levels of detail. Two parallel predictions were prepared in SAIL:

- Simplified simulations prepared by Hochschule Jade and Geesthacht Zentrum Helmholtz – Essentially the focus of these simulations is to be able to very quickly check the potential of routes, rigs or ship speeds. The simulations only account for the thrust produced by the wind (assisted) propulsion. These are described in section 4.
- Detailed simulations prepared by MARIN. The focus of these simulations is to be comprehensive. It is attempted to cover all elements that may affect performance, also include voyage optimisation. The focus of these simulations is therefore to be accurate and to be able to see how each component of the system performs.

MARIN performed detailed simulations for the Ecoliner. The methodology is explained first, then followed by simulation input information, scenario and environment. Finally the results are discussed.

9.1.1 Methodology

Comparison to reference vessel

Mostly the interest of these voyage simulations is to calculate the fuel consumption of a wind assisted vessel and compare this against a reference vessel to determine savings. The selection of a reference vessel is very influential in the end result. The primary basis is the reference vessel should be of modern design and have and identical payload and nominal speed. It can then be expected to have the same earning capacity. The comparison is then purely based on costs of which the fuel cost is a prominent part. This does however still allow many options open for comparison vessels. The selection will therefore be a bit arbitrary. For the simulations at MARIN with the Ecoliner it was decided to simply take the exact same vessel, but to remove the sails and rig. It is noted that this means that the reference vessel already has a slightly specific hull shape and propulsion installation.

GULLIVER

At MARIN the program GULLIVER is available for so-called ship route scenario simulations. It simulates the operation of a ship on a fixed route over a long period. The basic elements are the ship's calm water and seakeeping characteristics, the environment (wind, waves, current) and an operational scenario representing the captain's reaction to actual conditions. A set of Matlab scripts is used to prepare the simulations and to combine, post-process, select the best trip for each departure and gather statistics.

The focus of GULLIVER is to generate results for a large number of departures (in the order of hundreds) spanning a long time duration (in the order of years) such that a favourable statistical uncertainty is achieved for the performance on a specific route.

Speed and route optimisation

Pre- and post-processing of GULLIVER allows speed and route optimisation. This was assumed to be important as a wind assisted ship may need to anticipate actual weather conditions to make best use

of the wind. A grid is designed for each route. This grid consists of waypoints (the intersections where routes cross) and legs (the sections of the routes between the nodes). For each departure date, all individual segments are simulated at all different times that a ship could theoretically pass there. Additionally, this is done for three speeds per leg. After all these individual simulations are conducted, these are used to compose all possible combinations to do the trip, under the following constraints:

•   The ship arrives on time at the end destination

•   The passage through a node should be possible: i.e. the ship should not leave earlier on the next leg than the arrival on the previous leg

From this entire set of simulations for every individual departure date, simply the best realisation is selected. It is noted that this simulation method effectively assumes that the captain already knows before leaving what the actual weather on the route will be. It is of course clear that in reality this will not be the case and consequently performance will likely be lower.

Output

Figures showing each time step on a simulation are made for any variable as calculated by GULLIVER, for both the conventional and wind assisted ship and for all three routes. The data included is each individual time step from the voyages that turned out to be the most efficient for a certain departure date. The dataset being so large decreases its statistical uncertainty. See the figure below as an example. Some explanations follow here per labelled plot:
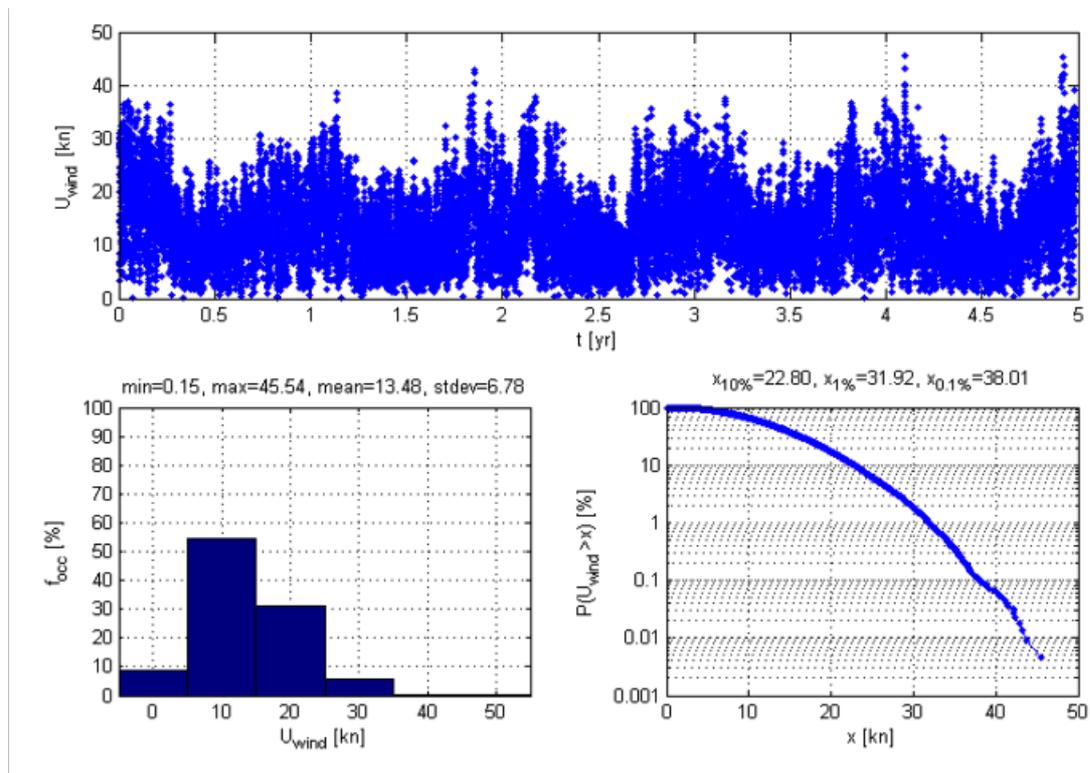
Roadmap for Sail Transport: Engineering

1.   Time trace: This plot shows the entire time trace of all time steps over the entire simulation duration of one year. The plotted points are very dense because the time scale is large and several ships are effectively on the same route simultaneously.

2.   Histogram: This plot shows a histogram in which the frequency of occurrence of a certain value can be read, along with some statistics at the top of the plot. In the present example it shows e.g. that the mean wind speed is 13.48 kn and the wind speed is between 5 and 15 kn about 54% of the time.

3.   Distribution: This plot shows the probability of exceedance of a particular value on a log scale. In the present example it shows that there is a 1% chance for the wind speed to exceed 31.92 kn.

All graphs are available in a data report.

Sankey diagrams

Based on the results, some further plots are prepared highlighting specific trends that are considered relevant. This includes Sankey diagrams . These Sankey diagrams graphs serve to graphically show the proportion of all energy flows. The thickness of each arrow is proportional to its energy flow. The total energy input is identical to the total energy output. The values refer to the average level over one year of data from one specific route and ship configuration. An example is shown in Figure 9-1 with some indications.
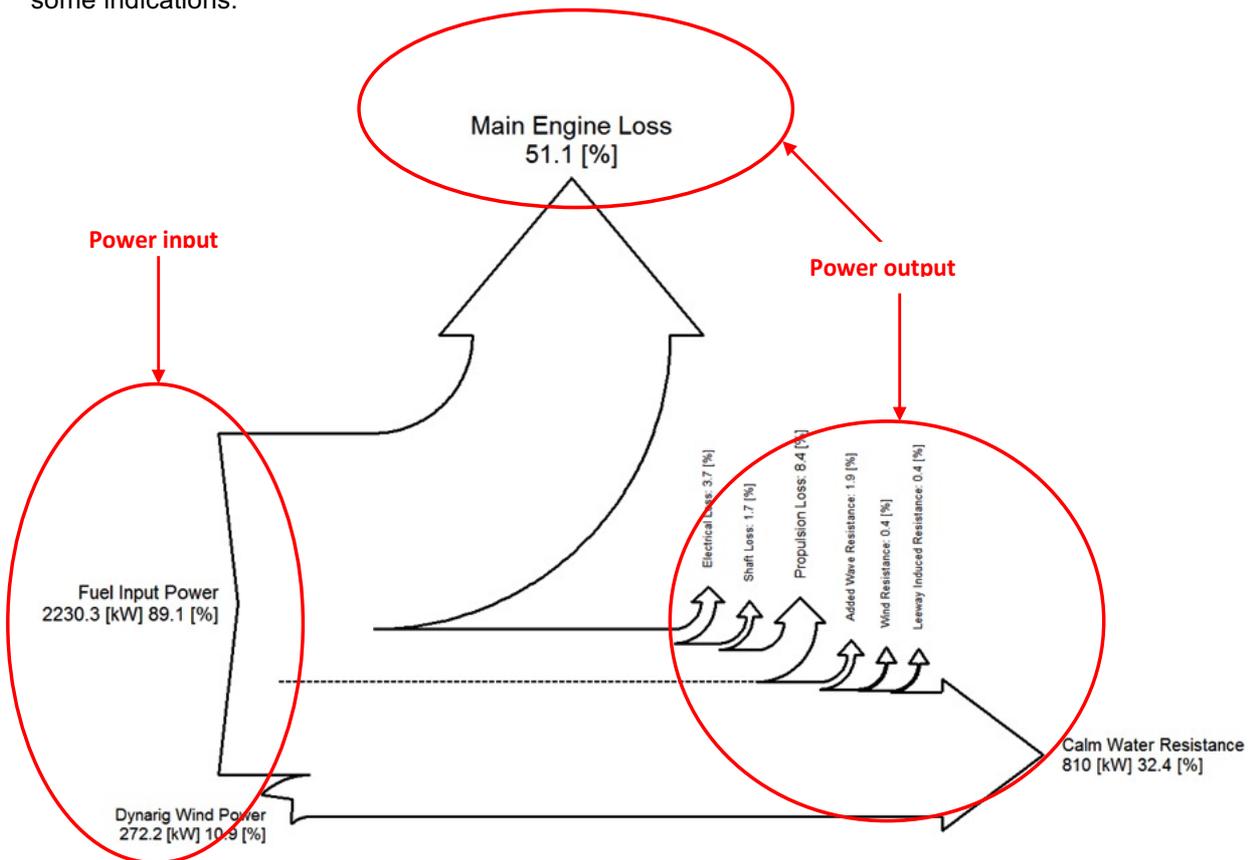

Figure 9-1: Sankey diagram

9.1.2 Vessel particulars (simulation input)

GULLIVER requires input regarding:

- Hydrodynamic forces: resistance, lift and lift induced drag
- Aerodynamic forces: lift and lift induced drag, target lift coefficients/trim and the effect of reefing
- The power generation and propulsion installation
- Seakeeping performance: stability, mass inertia radii, roll damping, freeboard height and location of wheel house
- Added resistance (due to waves)

One is referred to MARIN for an extensive overview of input used. As a summary, the following particulars were used for the Ecoliner:

- Hydrodynamic forces delivered by DNA based on CFD calculations. The vessel was at a draught of 7.2 m. The rudder was neglected. In retrospect is also proved that one allowance was not applied which led to a slight under prediction of resistance. The effect on percentage reduction of resistance and fuel consumption between a conventional and wind assisted vessel is expected to be negligible.
- Aerodynamic forces were based on the Wolfson Unit wind tunnel experiments (see section 7). Form the tested configurations, 3 mast Dynarig with a total sail area of 3859 m[2] was selected. The base windage of the hull was however based on coefficients of Blendermann[24] with a frontal projected area of 214 m[2].
- A controllable pitch propeller with a diameter of 4.25 and a design pitch-diameter ratio of 1.2. The Wageningen C-D-series was used to calculate performance for alternate pitch-ratio's with steps of 0.2 and up to 1.4.
- The power generation was diesel-electric with four diesel generator sets each with maximum power of 750 kW and run at constant rotation rate and maximum 90% of its installed power. An electric propulsion motor is assumed to run the propeller. The efficiency of the two power conversions (mechanical-electric and electric-mechanical) were each assumed to be 90%. Auxiliary power was not modelled in these simulations.
- Seakeeping calculations were done at MARIN using SHIPMO.
- Added resistance calculations were done at MARIN using the SPA Wave method[25] and the SHIPMO calculation results.

9.1.3 Environment and scenario

Three routes were simulated in both directions. They are shown in Table 9-1 and Figure 9-2.

Table 9-1: Routes (simulated in both directions)

	Departure port	Arrival port	Distance [Nm]	Sailing time @ ≈ 11 kn
1	Aberdeen	Oostende	389	37 h
2	Gibraltar	Skagen	1760	161 h
3	Gibraltar	Trinidad	3328	306 h

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[24] W. Blendermann, *Wind Loading of Ships - Collected Data from Wind Tunnel Tests in Uniform Flow*. Institut fuer Schiffsbau der Universitaet Hamburg, 1996.

[25] R. Grin, "On the Prediction of Wave-added Resistance with Empirical Methods," *Journal of Ship Production and Design*, 2015
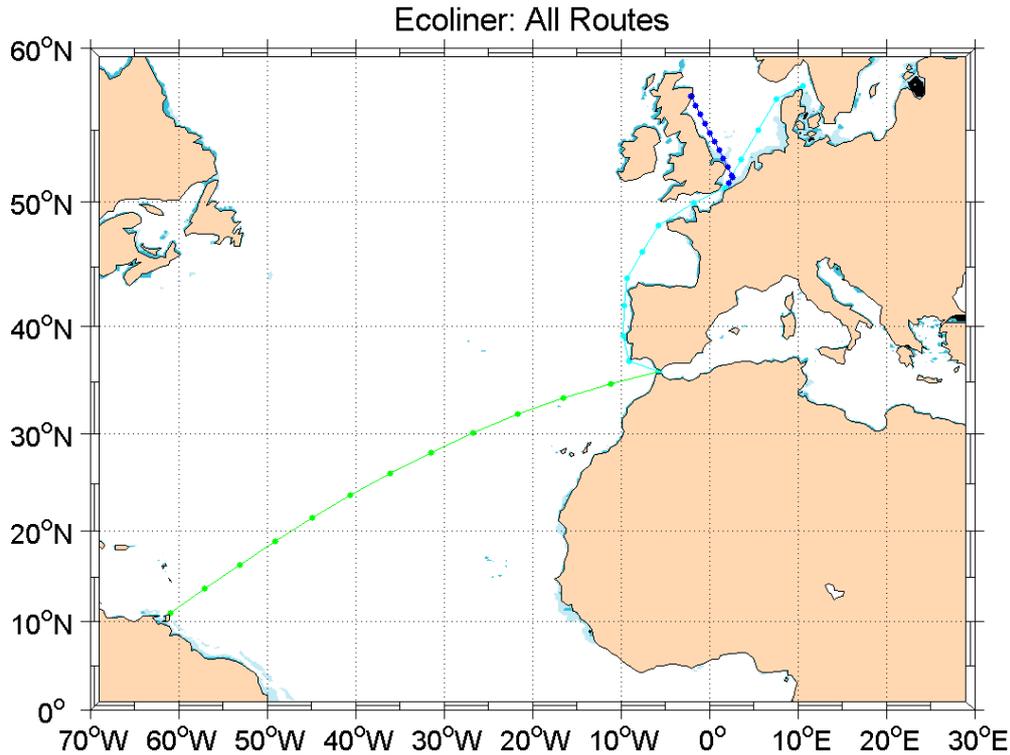
Figure 9-2: Routes

The simulations were conducted for the full years of 1995 through 1999. A ship departure was modelled every three days, such that the route was always covered with several ships in parallel. A simulation time step of between 1 and 3 hours was used depending on the route.

Speed, sail propeller control

During the voyage simulations, various parameters are controlled to realise realistic voyages:

- **Speed control:** Firstly, within the grid points, the vessel operates on a just-in-time scenario. The vessel adjusts its engine power in order to arrive at a designated time to the next grid points. Note, that each leg in the grid is simulated with multiple average speed options.
- **Sail control:** The optimal overall lift coefficient (related to mast rotation) was determined per wind angle and speed prior to voyage simulations. During the actual simulations, the reef parameter was determined in order to constrain the vessel to a maximum steady heel angle of 10 deg.
- **Propeller control:** For each time step, the most optimal propeller pitch ratio was determined.

Wind, waves and current

Wind and wave data from 1990 to 1999 with a half degree grid and 1 h time step was used. It covers the area shown in the image below.
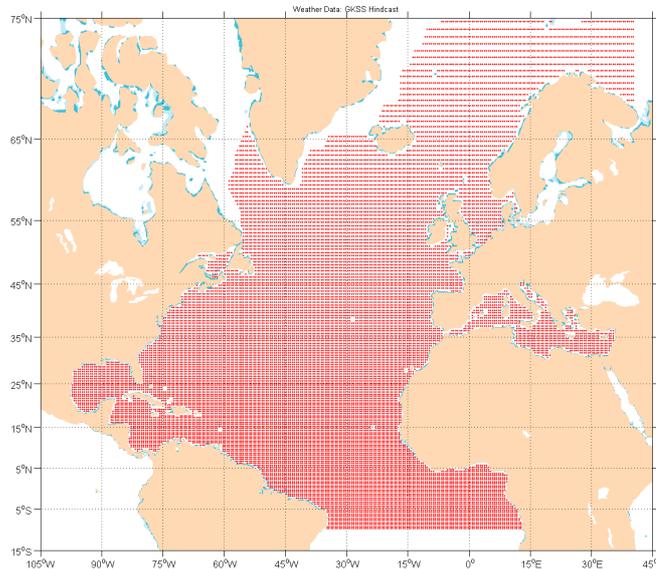
Tidal current has been included for the Gibraltar-Skagen and Aberdeen-Oostende routes. The tidal currents are obtained from TOPEX/Poseidon inverse tidal model[26] of Oregon State University, USA.

Ocean current has been included for the route Gibraltar-Trinidad. These ocean currents were taken from OSCAR[27], which provides worldwide ocean surface currents with a 1° resolution and a 5-day interval. This database is based on satellite altimeter and scatterometer data.

9.1.4   Results
One is referred to MARIN for a detailed discussion of all individual. The overall main results are included here.

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[26] "OSU Tidal Data Inversion." [Online]. Available: http://volkov.oce.orst.edu/tides/. [Accessed: 26-Feb-2015]

[27] Ocean Surface Current Analysis – Real Time (OSCAR), F. Bonjean and G.S.E. Lagerloef, *"Diagnostic Model and Analysis of the Surface Currents in the Tropical Pacific Ocean"*, Journal of Physical Oceanography, Vol. 32, No. 10, pages 2938-2954, 2002

www.oscar.noaa.gov

The resulting fuel consumption for the conventional and wind assisted vessel is shown in Figure 9-3. The results show that savings between 10% and 40% can be achieved on fuel consumption as follows:

10%: Trinidad-Gibraltar (unfavourable route)

25%: Most routes

40%: Oostende-Aberdeen and vice-versa

It is interesting to see that it is not the trans-Atlantic crossing that gets the best results, although that route is traditionally regarded as a suitable route for sailing vessels. The higher savings on the route Oostende-Aberdeen can be attributed to the higher apparent wind speeds on average (even if the typical apparent wind angle is worse than on the route Gibraltar-Trinidad).
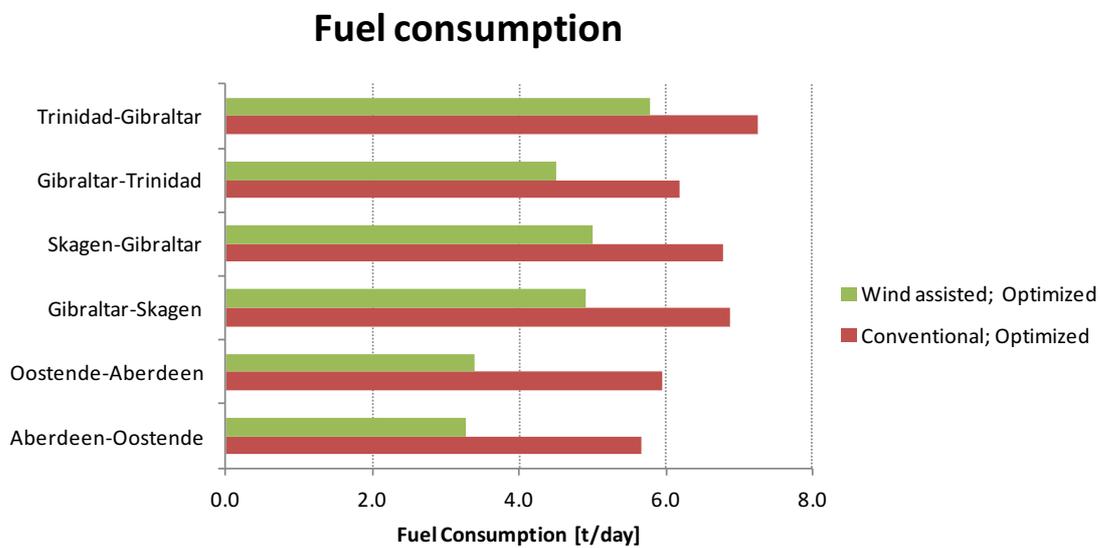
Fuel consumption

Figure 9-3: Overall fuel consumption

10   Living Labs

Avel Vor Technologie (AVT) designs and test innovative concepts for hybrid ships. While the concepts described in the previous sections focus on new ship designs, Avel Vor focuses on improving the ecological performance of existing ships. These ships will not be as efficient as special designs, for instance it was shown in section 6 that optimal usage of wind power is obtained from optimized hull forms. But since ships have a long live-span quick reductions in emissions can only be achieved if existing ships are retrofitted. A second argument pro retrofitting focuses more on the economy and politics: retrofitting may improve the performance of small ships and help to revitalize small or medium size ports as well as regional and interregional maritime connections. These two considerations lead to reverse the paradigm: rather than seeking the optimization of a new boat for a given hybridization type, it is better to look for the best hybridization for a given ship. This approach is pursued for instance in the FP7-TRANSPORT project Ulysses.

AVT operates laboratory ship, the "Grand Largue" (Fig. 10.1). The Grand Largue is a wooden trawler, 16 meters long and 5,42 meters wide, built in 1981. Its main propulsion is provided by a diesel engine, Baudouin 6R124SR, with a power of 320 kW at 1900 rpm. Its maximum speed is 9,6 knots, but this speed is characterized by a very high fuel consumption. The usual speed is in the range of 6.5-8 knots which corresponds to 60 to 80% of the engine power. Since 2010, this ship has an auxiliary propulsion system consisting of three sails mounted on two bipod masts, whose total area is 90 m^2, which is relatively low for a vessel of this size. The sails act as auxiliary drive for the main engine. Several experiments were done to find the optimal strategy for the use of wind power. During the experiments wind speeds were between 10-15 knots. In tables 10.1 the rpm was kept fixed, the speed was left floating under the different wind conditions. In table 10.2 the engine was controlled such that the speed remains constant. Quite clearly the latter approach gives higher power savings.

RPM	sails	litres/hour	speed	litres/mile	gain
1250	no	50	6.3	4.92	
1250	yes	28,5	7.4	3,85	22%
1450	no	63	7.4	6.75	
1450	yes	41	8.1	5.06	25%

Table 10.1: Fuel savings due to sails for constant RPM settings on the Grande Largue.

speed	rpm	sails	litres/hour	litres/mile	gain
7,4	1450	no	50	6,75	
7,4	1250	yes	28,5	3,85	43,00%
8	1600	no	63	7,87	
8	1450	yes	41	5	36,00%

Tab. 10.1- Fuel savings due to sails at constant speed on the Grand Largue

Within the SAIL project a new control for the wind assisted propulsion system (WASP) on the Grande Largue was designed. The previous system allowed to control the sails from the bridge but was complicated to handle because a single hydraulic system commanded the three sails. The new second generation system is more ergonomic and safer: new sensors allow to monitor both the

wanted and the actual position of each control. The new user interface allows to manage the auxiliary sails without having sail training.

Another topic is the development of a soft wing sail. Rigid wing sails are well known and used for instance on the Japanese ships described in section 2. Wing sails are shaped like aircraft wings, sometimes these are called thick sails. Wing sails feature rather high propulsion coefficients. However, rigid wing sails cannot be reefed under bad weather conditions and are therefore potentially dangerous for a commercial work boat. The soft wing sail (Fig. 10.2) combines the high performance of a profiled wing with the ability to be reefed or even to be hauled down.

The sail itself is designed by the naval architect A. Oriot, it has two slots and one reefing only to keep it simple. This sail-wing will be fixed on a rotating carbon mast, mast calculations are in progress. A computerized control utilizing a two axis joystick is designed by F. Gellert. The design of the sail is finished, the system is going to be installed on a catamaran (Fig. 10.2) in spring 2016.

Fig. 10.1: The Grande Largue, the living lab of Avel Vor Technology.

AVT is currently studying an electrically assisted ship propulsion system (EASP). The idea is to add an electric motor and a set of batteries to a conventional diesel engine. The system can operate in four modes

- electric motor alone: especially during port manoeuvres and at low speed avoiding the low efficiency of the diesel engine at low speed.
- diesel engine alone: chosen if the engine is operated close to the optimal specific fuel consumption
- combined mode: the electric motor boost the diesel engine in case of large power demands
- charging mode: the electric motor charges the batteries

The key point is the price and the energy density of the batteries. The current development of energy storage devices leads to falling prices and smaller batteries. It is expected that EASP will be viable in a few years. Adding wind power to such a system creates the wind-electrically assisted propulsion system (WEASP). These system offers very interesting opportunities: since wind generates parts of the propulsion power in a traditional WASP, low power operation at low efficiency becomes more probable. In this situation an electric motor would increase the overall efficiency. The Grand Largue will be the first WEASP tri-hybrid vessel and allow to study the characteristics of such a system.
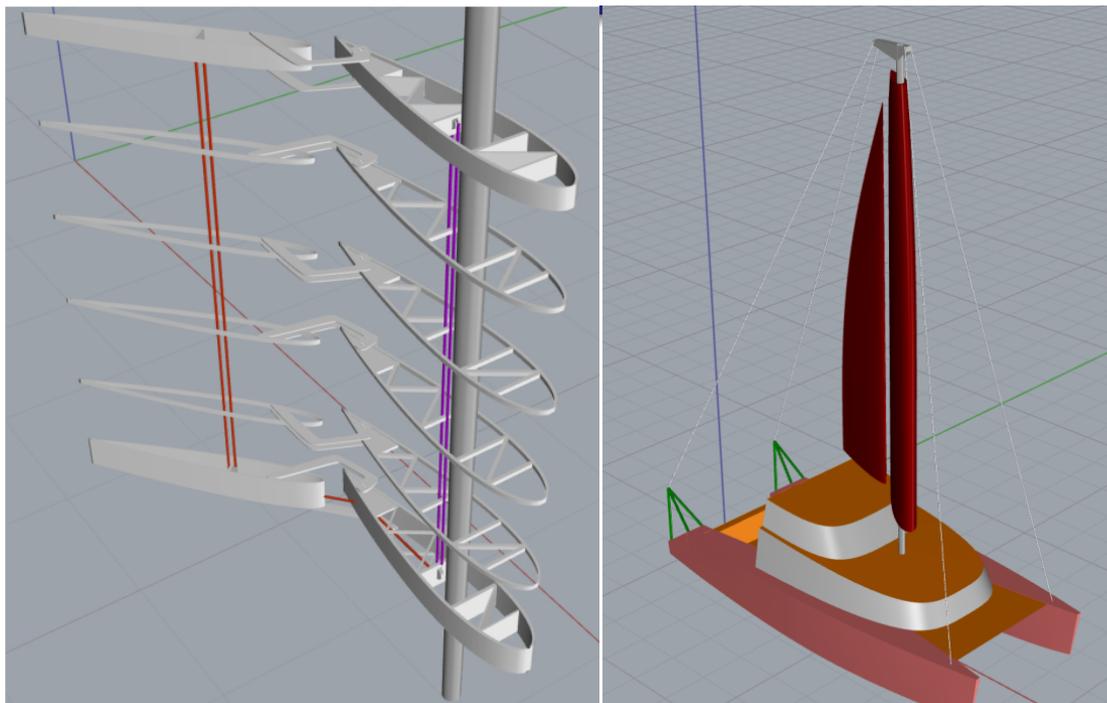

Fig. 10.2: Sketch of the soft wing sail. The catamaran (length 9.20m) on the right panel will be equipped with the sail and the joystick control in spring 2016.

11 Appendix

### 11.1 Coefficients for different wind propulsion systems

Bermuda main sail
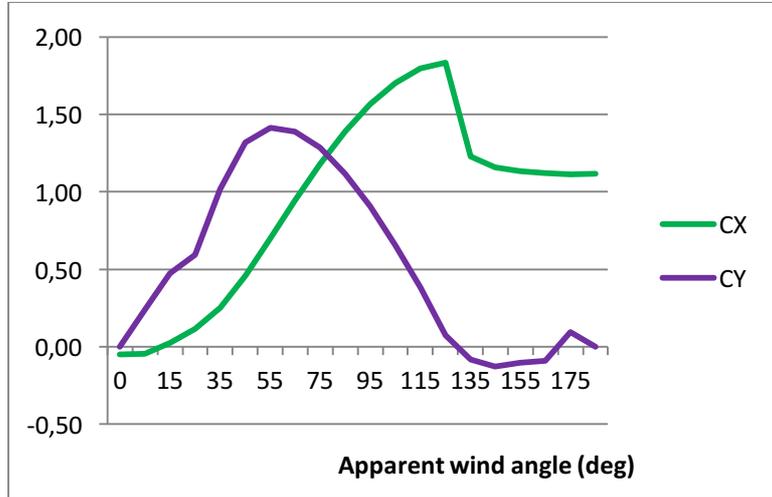
Dyna Rig
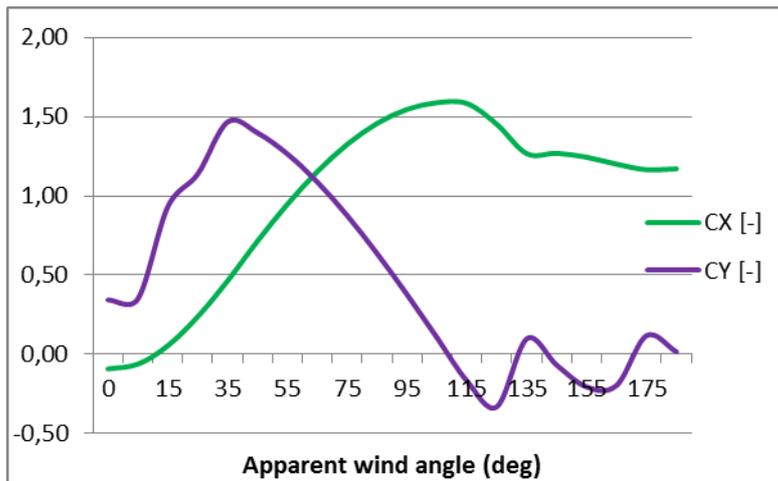
Autares
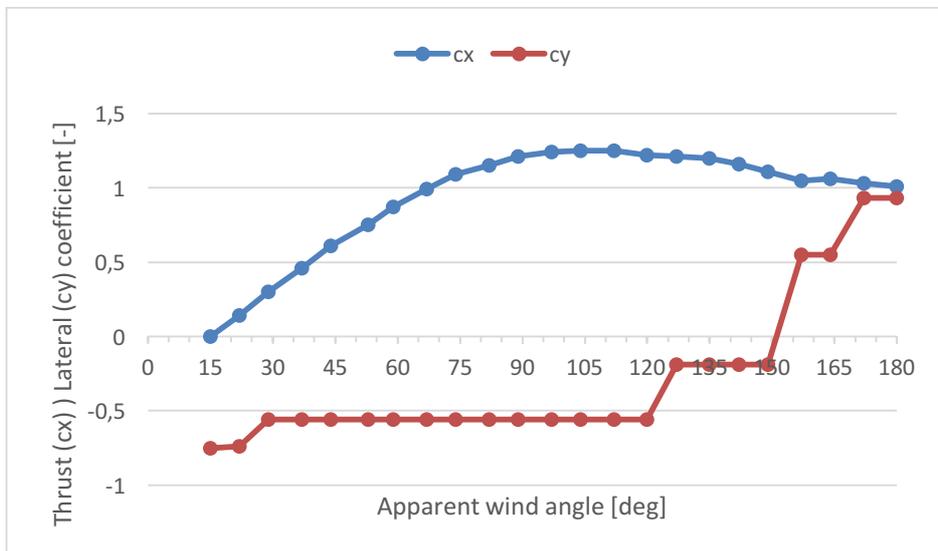
Wing sail
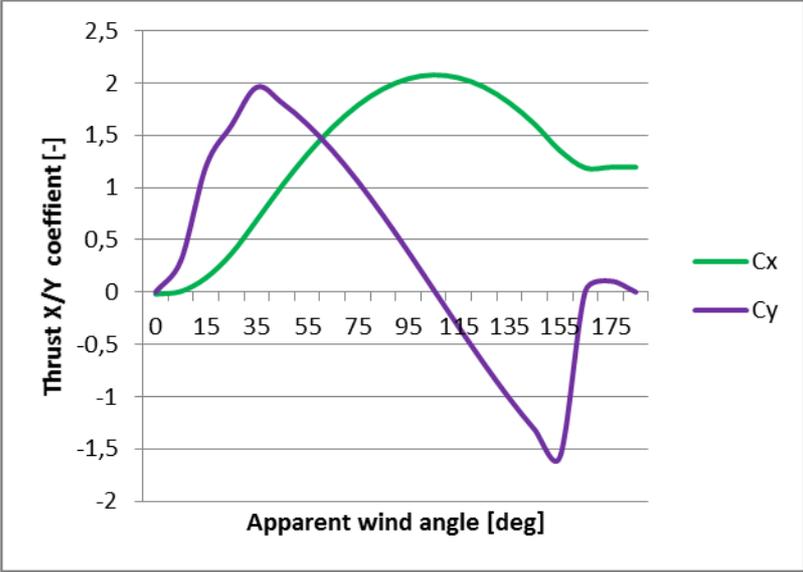
Multi Wing sail
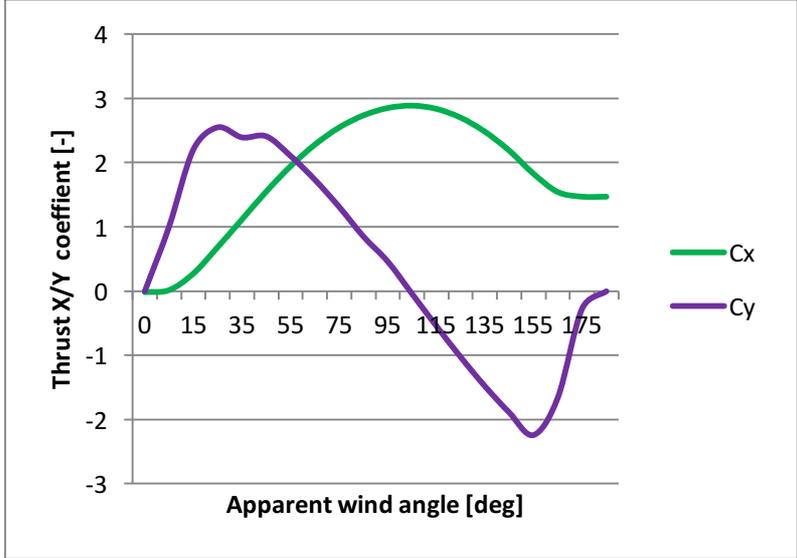
Flettner rotor
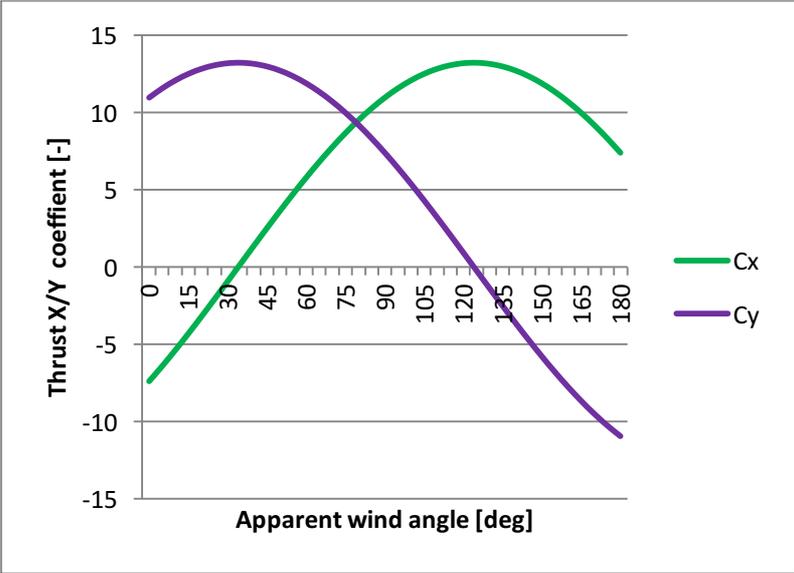
Turbo sail
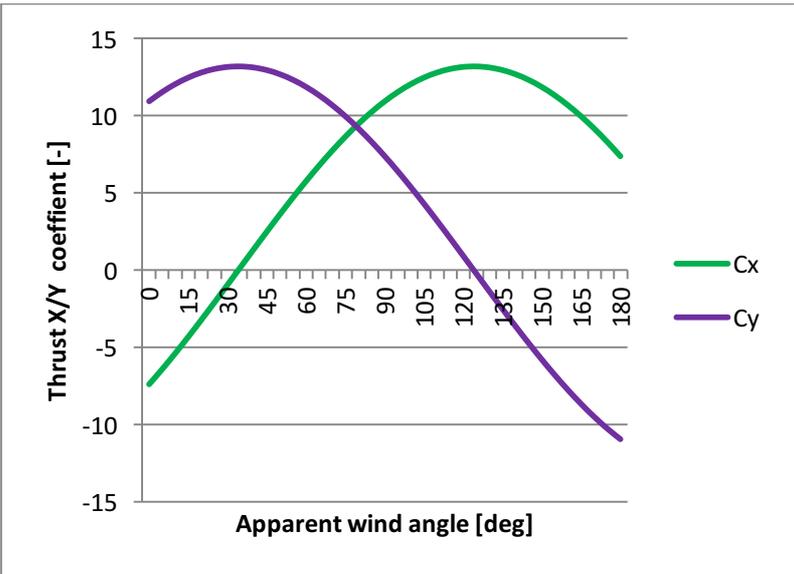
EU Interreg IVB SAIL partnership

1 - Province of Fryslân
3 - Plymouth University
4 - Jade Hochschule
5 - Helmholtz-Zentrum Geesthacht
6 - Aalborg University
7 - North Sea Foundation
8 - Fairtransport Trading and Shipping
9 - Municipality of Harlingen
10 - C-Job

11 - Ameland Shipping
12 - NHL Northern University
     of applied sciences
13 - MARIN
14 - E&E consultant
15 - Avel Vor Technology
16 - Port of Oostende
17 - ECO Council
18 - World Maritime University

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